# Establishing Alvar Mosses on Quarry Floors:

## A Necessary Step in the Restoration of Quarries to Alvars

Newly established *Tortella tortuosa* moss colonies readily visible against the grey bare limestone of an experimental site.

Summary Report

Suzanne Campeau
Bryophyta Technologies inc.

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bryophyta

**SUMMARY OF FINAL REPORT**

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# 1 Introduction

*Figure 1. The nearly bare floor and walls of a quarry where extraction activities ceased more than fifty years ago.*

## Context

Numerous abandoned limestone quarries exist in Southern Ontario. The Ontario Aggregate Resources Corporation (TOARC), through the Management of Abandoned Aggregate Properties (MAAP) program is responsible for the rehabilitation of some of these quarries that were abandoned prior to 1990. The MAAP program also funds research that will provide new insights on how to better rehabilitate depleted sites, a topic of interest to the Aggregate Industry as it would help producers rehabilitate their sites following extraction activities.

Contrary to gravel pits where rehabilitation is generally straightforward, limestone quarry floors present a number of challenges to revegetation, including very shallow or non-existent soils and harsh environmental conditions. Returning quarries to prairie or forest habitat would necessitate the placement of large quantities of topsoil, a costly option. Is there an alternative? Could former limestone quarries be turned into another, valuable habitat, potentially with less effort and at a better cost?

## Alvars

Alvars are natural communities that occur on flat, open areas of limestone or dolostone bedrock with a sporadic, thin soil cover. Alvar vegetation is a unique mixture of stunted trees, herbs, forbs, mosses and lichens (Schaefer 1996). Not all alvars are alike: some are bedrock pavements with almost no soil, others are on thin soil and their vegetation is more grassland or savanna-like. They are all subject to seasonal drought (Alvar Working Group 1999).

Almost all of North America's alvars occur within the Great Lakes basin. Approximately 64% of Great Lakes alvar area occurs within Ontario, 34% are found in New York, Michigan and Ohio and the remaining few, smaller areas are located in Wisconsin

*Figure 2. Mosses, low shrubs and stunted trees of an alvar of the Bruce Peninsula, Ontario.*

and Québec (Alvar Working Group 1999). Alvars are only sparsely distributed in the landscape and were likely always so. Catling and Brownell (1995) estimated that their extent in southern Ontario prior to settlement was between 1100 and 1500 $km^2$. The International Alvar Conservation Initiative of the Great Lakes Program of the Nature Conservancy documented approximately 112 $km^2$ of remaining alvar habitat of reasonable quality across the entire Great Lakes basin, a mere 10% of their original area (Alvar Working Group 1999).

*Figure 3. An alvar on the Bruce Peninsula, Ontario.*

Despite their low plant biomass, the bedrock pavements, grasslands and savannas that constitute alvar ecosystems are of great value from a conservation perspective. Alvar habitats are floristically rich, containing an even larger number of species than the surrounding forest habitats and harbouring a large proportion of bryophytes (i.e. mosses, liverworts and hornworts) and lichens (Schaefer and Larson 1997).

The vegetation of alvars is very distinctive and is composed of an unusual blend of boreal, southern and prairie species, including many that are far from their normal range but able to survive in shallow soils and harsh conditions (Alvar Working Group 1999). Many of these species are of global or regional significance. In Ontario for example, the flora of alvars contains a large number of unusual, rare and even endangered native species (Alvar Working Group 1999; Catling and Brownell 1995; Schaefer 1996 and references therein).

The fauna of alvars is as distinctive as its vegetation (Alvar Working Group 1999). Alvar habitats have characteristic species of reptiles and birds associated with them, including the threatened eastern massasauga rattlesnake and the endangered loggerhead shrike. Alvars are also home to a number of rare or unusual insects and snails.

# Restoring Quarries to Alvars

From 2003 to 2006, researchers from the University of Guelph, funded through the MAAP program, conducted the Quarry to Alvar Initiative (Larson et al. 2006), an innovative research project aimed at assessing the potential for restoring abandoned limestone quarry floors to alvars.

Results obtained by the University of Guelph Quarry to Alvar Initiative were very promising. These researchers showed that naturally regenerating abandoned quarry floors were strikingly similar to alvars, both physically and in term of species of vascular plants present (Larson et al. 2006). They also showed that if certain alvar species are not present on quarry floors, it is likely because their seeds do not reach this potential habitat. Once seeded on a quarry floor, alvar plants established readily, requiring nothing more than the possible addition of sand.

The advantages of restoring quarries to alvars would be two-fold. For one, because many alvar species are rare or endangered, rehabilitated quarry floors could then become habitat extensions for these species. In addition, the development of a simple but effective

*Figure 4. The weathered floor of an old quarry, with mosses and other plants growing along the cracks of the limestone pavement.*

methodology to rehabilitate alvar communities on depleted limestone quarries may reduce the need for costly and fuel-consumptive rehabilitation alternatives such as the importation and placement of large quantities of top soil while still resulting in the restoration of a highly valuable natural habitat.

The end results would be a lower-cost, smaller carbon footprint methodology for quarry operators to rehabilitate their sites as well as an increase in available habitat for alvar species.

# Mosses and Quarry Restoration

Bryophytes are an important component of alvar vegetation, not only in terms of biodiversity, but also in terms of the role these plants play at the ecosystem level. Schaefer and Larson (1997) recorded 50 species of bryophytes - 40 species of mosses and 10 species of liverworts - in their surveys of Ontario alvars.

Yet, of all the groups of plants – vascular plants, bryophytes and lichens – that are characteristic of alvar vegetation, bryophytes were shown by the University of Guelph Quarry to Alvar Initiative research team to be the most poorly represented on depleted quarry floors. In total, only 14 species of bryophytes were recorded in the 13 quarries surveyed. In 4 of these quarries, no bryophytes were recorded on the sampling plots.

Mosses are known as pioneer species that can establish on very poor, bare mineral surfaces and rock pavement. Once established on limestone, moss cushions will retain humidity, provide organic material through plant growth and death, help catch particles, nutrients and seeds that would otherwise be washed away, and generally contribute to soil building processes. The water retention capacity of bryophytes may also increase system resilience against drought. All of these elements should in turn promote and enhance alvar vascular plants establishment and survival.

Consequently, establishing bryophyte communities on limestone pavement is a very important component in the successful restoration of quarry floors to alvars. Without mosses, restored quarry floors would simply not compare to natural alvars.


*Figure 5 Sampling quadrat used in alvar and quarry plant surveys conducted by University of Guelph researchers. Image: J.A. Gerrath.*

# 2 Project Description

*Figure 6. View of Lawless Quarry, taken from the top of one of the cliffs. At the right, the pool on the lower level quarry floor.*

## Research Objectives

The overall objective of this project was to determine how alvar moss species could be successfully established on quarry floors on the assumption that they are an important component of functional alvar plant communities.

The research was intended to provide recommendations for simple and affordable methods that could be used to promote and accelerate the establishment of alvar moss species on depleted quarry floors.

## Approach

The approach used in this project combined:

1. Analyses of already existing quarry and alvar vegetation survey data to determine which species to use and which environmental factors could be manipulated at the quarry floor level to enhance moss establishment;
2. A series of field experiments on how to establish alvar mosses on limestone quarry floors.

In order to ensure that our conclusions could be extrapolated to a variety of sites and field conditions, experiments were replicated among a number of quarries located across southern Ontario and in different years and seasons.

Field experiments were conducted on a small-scale due to limitations in source material. Special attention was nonetheless given to large-scale applicability and to compatibility with the methods suggested in the Quarry to Alvar Initiative Report for the establishment of alvar vascular plants in quarries (Larson et al. 2006).

## Analyses of Existing Vegetation Survey Data

The data sets used for these analyses encompass data collected from seven natural alvars (Schaefer and Larson 1997) and nine abandoned limestone quarries of various age (Tomlinson et al. 2008) in southern Ontario. With the researchers' permission, we extracted the information pertaining to bryophytes from the larger vegetation datasets in order to run statistical analyses on this component alone.

The results of these analyses were interpreted to determine:

1. Environmental preferences of individual bryophyte species to select candidates for restoration projects;

2. Environmental factors that play the most important role for mosses, in order to address these factors in our field experiments.

# Field Experiments

## Objectives

The objectives of the field experiments conducted during this project were:

1. To investigate whether targeted species of alvar mosses can successfully establish after the introduction of moss propagules to quarry floors;
2. To determine which environmental factors need to be manipulated or alleviated at the quarry floor level to allow or enhance moss establishment and how this can be accomplished by rehabilitation practitioners.

## Experimental sites

A total of eight moss introduction experiments were conducted in four quarries located across southern Ontario (Figure 8).

Details on individual sites are provided in the full Project Final Report (Campeau, 2013). To give the reader a general idea of the different sites, pictures of the four quarries are provided in Figure 6, 7, 9, 10 and 11 of the current report.

*Figure 7. View of bare rock and thin mineral substrate at Hendry Quarry. At left, a shallow pool in a lower area at the base of the cliffs.*

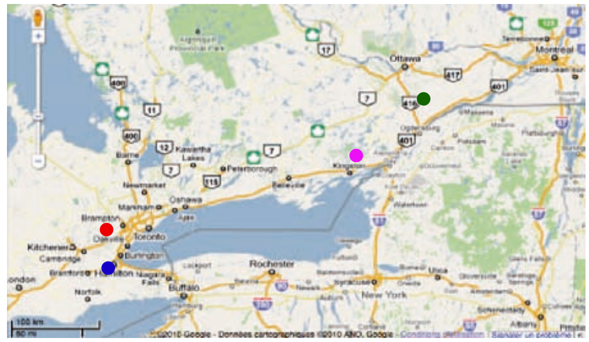


*Figure 8. Location of the experimental sites. ● Lawless Quarry; ● Hendry Quarry; ● Fletcher Creek Quarry; ● Toth Quarry.*

## Timeline

The first field experiment was initiated in south-eastern Ontario in June 2008, followed by more experiments in August 2008, October 2008, October 2009 and August 2010. Data on the different experiments were collected each fall from 2008 to 2012. Each experiment was monitored for at least two years (Table 1).

## Species used

Analyses of alvar and quarry vegetation surveys suggest that species that "bridge" the conversion of quarry to alvar are the most suited for the initial stages of rehabilitating quarry floors as they are likely to establish without extensive site modifications. Based on this, four species of mosses that inhabit early successional 'rocky' habitat were selected for the study (Figure 12).

Three of the selected species are mosses that are found on limestone pavement in alvars but also occur in depleted quarries: *Tortella tortuosa*, *Syntrichia ruralis*, and *Schistidium rivulare* (Larson et al. 2006).

The fourth species was *Encalypta procera*. This species is found in alvars (Schaefer 1996) but was not recorded in the quarry vegetation surveys conducted by University of Guelph researchers (Larson et al. 2006). Our team found *E. procera* at Fletcher Creek Quarry on an old, well-vegetated

*Figure 9. Bare weathered limestone pavement at the Fletcher Creek Quarry "Old Site".*

*Figure 10. Patches of bare limestone and thin mineral soil at the Fletcher Creek Quarry "Young Site".*

limestone ledge bordering a pool. Therefore, although this occurrence shows that *E. procera* can sometimes be found in old quarries, this species does not appear to colonize quarry floors readily, making it an interesting candidate for the current study.

## Factors studied

According to the analyses of alvar and quarry vegetation surveys, soil depth, moisture and degree of exposure are important and potentially modifiable factors that determine the distribution of moss species in alvars and quarries. Based on these findings and on our own knowledge of factors that affect moss establishment in other habitats, three environmental factors were selected for field experimentation:

1. the type of substrate;
2. the use of a protective mulch cover, and;
3. changes in microtopography made to create a sheltered environment for mosses.

A total of eight moss introduction experiments were conducted in the four quarries. Most experiments included more than one environmental factor, two or more species, and all were monitored for at least two years. This allowed the analysis of interactions between species, environmental factors and time since introduction.

Table 1 summarizes the factors that were addressed in each of the eight experiments. Details on each of these factor are provided in the next paragraphs.

### Effect of moss introduction and comparison between moss species

Two experiments conducted early in the project included a control where moss propagules were not introduced. Propagules, or diaspores, are any portion of a plant (e.g. seeds, cuttings, spores, fragments, etc.) that can produce an individual once detached from the parent plant. The control was used to determine whether moss establishment from naturally occurring propagules—e.g. airborne spores—could be favoured by changing environmental conditions alone.

*Figure 11. View of the reworked cliff and floor surface at Toth Quarry.*

*Figure 14. Schistidium rivulare.*



*Figure 12. Top left: Tortella tortuosa, top right: Schistidium rivulare, bottom left: Syntrichia ruralis and bottom right: Encalypta procera.*

In all experiments but one, the responses of two or more species of mosses to one or more environmental factors were compared.

### Effect of a mulch cover

Seven experiments examined whether the addition of a straw mulch cover to protect introduced propagules improves moss establishment success. All straw mulch experiments included at least one other factor, such as substrate, topography or species, in order to determine if interactions existed between factors.

### Effect of substrate and amendments

Four experiments examined how moss establishment success on bare limestone compares to establishment in areas where a thin layer of mineral soil covers the bare rock. Another experiment examined how the addition of a thin layer of sand or of a sand and peat mixture influences moss establishment on bare limestone pavement.

### Effect of microtopography

One experiment examined how moss establishment success on bare limestone compares to establishment in areas where the limestone substrate is altered by heavy equipment to create a surface covered by broken rocks of mixed sizes.

Two experiments examined the effect of a sheltering topographical element consisting of low contour ridges made of small rocks on moss establishment success. This sheltering effect was compared to the effect of straw mulch.

**Table 1. Summary of the factors that were studied in the various experiments conducted during the present study[1].**

| Location | Experiment Initiated in: | Moss Species Used | Factors Tested | Monitoring |
|---|---|---|---|---|
| Lawless Quarry | June 2008 | *T. tortuosa*, *S. rivulare* and a control without mosses | Effect of substrate type (rock vs thin soil)<br>Effect of a straw mulch cover | 2008, 2009, 2010, 2011 |
| Hendry Quarry | August 2008 | *T. tortuosa*, *S. ruralis* and a control without mosses | Effect of substrate type (rock vs thin soil)<br>Effect of a straw mulch cover | 2009, 2010 |
| Lawless Quarry | October 2008 | *T. tortuosa*, *S. ruralis* | Effect of substrate type (rock vs thin soil)<br>Effect of a sheltering topography and comparison to the effect of straw mulch | 2009, 2010 and 2011 |
| Hendry Quarry | October 2008 | *T. tortuosa*, *S. ruralis* | Effect of substrate type (rock vs thin soil)<br>Effect of a sheltering topography and comparison to the effect of straw mulch | 2009, 2010 and 2011 |
| Lawless Quarry | October 2009 | *T. tortuosa* | Effect of substrate amendments (sand and sand-peat mix) | 2010, 2011 |
| Fletcher Creek Quarry - Old Site | August 2010 | *T. tortuosa*, *S. ruralis*, *S. rivulare*, *E. procera* | Effect of a straw mulch cover | 2011, 2012 |
| Fletcher Creek Quarry - Young Site | August 2010 | *T. tortuosa*, *S. ruralis*, *S. rivulare*, *E. procera* | Effect of substrate type (rock vs thin soil)<br>Effect of a straw mulch cover | 2011, 2012 |
| Toth Quarry | August 2010 | *T. tortuosa*, *S. ruralis*, *S. rivulare*, *E. procera* | Effect of substrate type (flat rock pavement vs broken up limestone rocks)<br>Effect of a straw mulch cover | 2011, 2012 |

*[1]A detailed account of the methods, results and conclusions for each experiment is presented in the Projet Final Report (Campeau, 2013).*

## Experimental designs

All experiments were conducted using standard factorial experimental designs. Exact designs varied based on the feasibility and convenience of applying a treatment to a single unit or to a group of units (split-plot designs). All experiments were conducted using 1 m x 1 m units at the centre of which a 50 cm x 50 cm area was used for moss introduction (Figure 13). This allowed a 50 cm wide buffer between introduction areas located in adjacent units. The moss introduction area was generally divided into four 25 cm x 25 cm quadrants that received different species of mosses.

*Figure 13. The 1 m x 1 m experimental unit used in all experiments. Moss introduction was limited to the central 50 cm x 50 cm area.*

## Experimental Methods

### Moss introduction

Moss colonies from the targeted species were picked by hand a day or two prior to moss introduction (Figure 14) and kept in the dark or in the shade in breathable Ziploc™ vegetable plastic bags until used. Most species used in this study are easily detached by hands from limestone, requiring no special equipment. Species that are more strongly bound to the rock can be detached using simple tools such as a trowel.

The collected moss colonies were broken apart by hand into individual stems, clumps of a few stems and fragments of mosses. This material was then divided equally by volume among the number of experimental units to be established.

In all experiments, the ratio of collected material to covered surface was 1:8 (i.e. a 25 cm x 25 cm area of collected mosses provided propagules for eight 25 cm x 25 cm areas). Propagules were spread by hand, with care taken to ensure even distribution over the entire surface to be covered, including edges.

### Mulch treatments and mulch application

Straw mulch used in the experiments was purchased locally and was either oat, rye, spelt or wheat straw, depending on availability. The structure of the straw is more important than its type (oat, wheat, etc.), with long, unbroken stems providing a more efficient cover than straw that is chopped short or crushed.

Straw was applied by hand at a density that allowed light to reach moss propagules while still providing a sheltering cover (Figure 15). A few dead branches were placed on the mulch to ensure it would not be displaced by wind. Smaller sticks were placed on experimental units without mulch in order to create a windbreak and reduce the chances of propagules being blown away. Straw mulch covered the entire 1 m x 1 m surface of the experimental units to which

*Figure 14. Hand-collecting colonies of T. tortuosa. The green box is 25 x 25 cm and allowed us to measure the surface collected.*

*Figure 15. Two experimental units, one covered with mulch and the other not. Introduced mosses can be seen on the central 50 x 50 cm area of the unit to the right.*

it was applied (i.e. wider than the 50 cm x 50 cm moss introduction area).

### Substrate and substrate amendments

In the four experiments that examined the effect of a thin soil substrate on moss establishment (Table 1), a number of experimental units were positioned on bare limestone and compared to units located in areas where the limestone pavement was naturally covered with a thin layer of sand, gravel and fines (Figure 16).

In a fifth experiment we examined how actively adding a thin layer of soil amendments on bare rock would affect moss establishment. Two types of amendments were tested : horticultural sand and a mixture of horticultural sand and neutralized peat with a low nutrient starter charge (BM4 product, Berger Peat Moss Ltee, Saint-Modeste, Quebec). Prior to adding amendments, low contour rock ridges made of small rocks (product commonly referred to as ¾" clean limestone) were built around each experimental plot to prevent amendments from moving between adjacent plots (Figure 17A). The sand or sand and peat mixture were sprinkled on plots in an eight millimeter layer (8 L of amendment per 1 m x 1 m plot). Some plots did not receive any amendments. Propagules were introduced by hand in the central 50 cm x 50 cm area of each plot (Figure 17B). All were covered with straw mulch.

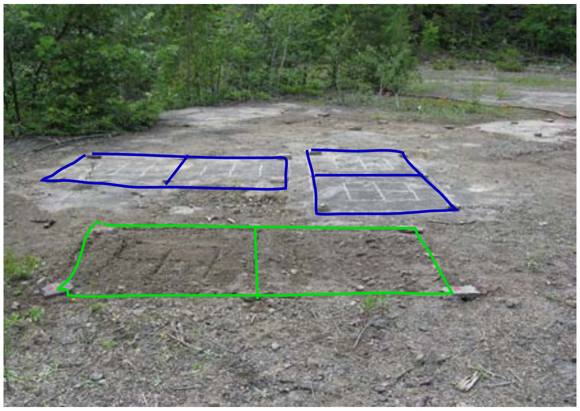

*Figure 16. Part of an experiment on the effect of substrate on moss establishment. Green plots are on thin soil, blue ones on bare rock.*

### Microtopography

The sheltering topographical element tested in the first experiments on microtopography consisted of a 100 cm x 50 cm rectangle that was delineated by a 5 cm to 10 cm high contour ridge made of small rocks (product commonly referred to as ¾" clean limestone) (Figure 18).

These experiments included three treatments: one with contour ridges and covered with straw mulch, a second with contour ridges without straw mulch and a third treatment with a straw mulch cover without contour ridges.

In another experiment moss propagules were introduced on plots located in areas of a quarry where the limestone substrate and adjacent cliffs had been reworked by machinery, leaving the substrate covered with rocks of various sizes. Moss establishment on these plots was compared to establishment on plots located on bare, flat rock areas (Figure 19). The experiment included plots with and without straw mulch for each type of substrate.

## Data collection

A 1 m x 1 m plastic frame with a 50 cm x 50 cm central opening was used for measurements (Figure 20). Ropes crossing at the center of the frame delineated four 25 cm x 25 cm quadrants.

With this frame in place, the surface area covered by moss in each quadrant was estimated visually. Any straw mulch remaining on the plots was carefully removed prior to taking measurements and replaced afterward. Measurements were made in the fall, at the end of the growing season. When necessary, plots were watered prior to measurement to ensure that moss colonies would be fully turgescent, with leaves spread out, so that measurements would be comparable from year to year. Images of each plot, subplot and sub-subplot were taken each time measurements were made.

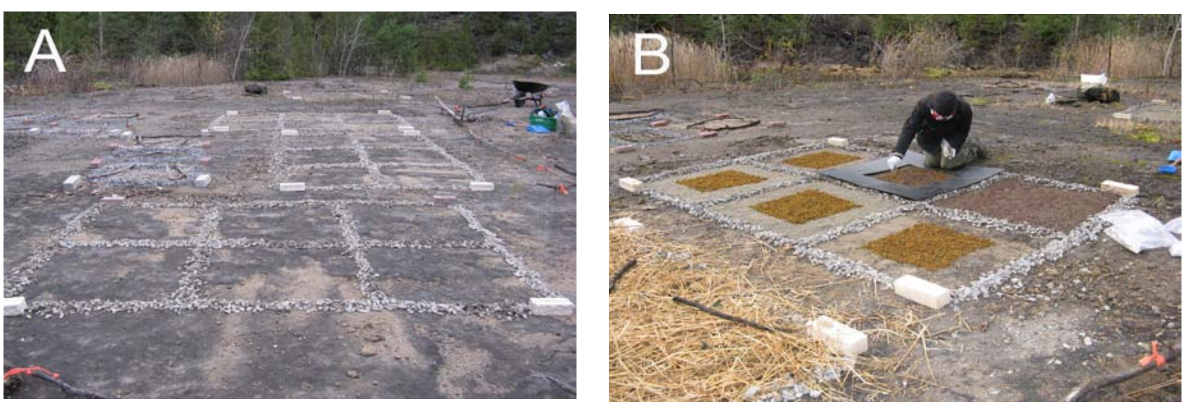


*Figure 17. Images of the Lawless 2009 experiment on substrate amendments. A) Contour ridges delineating experimental plots within a block. B) Introducing moss propagules on the central 50 x 50 cm area of a plot. Notice the grey (sand) and brownish (sand + peat) substrate amendments.*

*Figure 18. Images of the experiments on the effect of a sheltering topography. Left: experimental plot with subplots showing contour ridges and moss introduction areas with two species. Right: two subplots, one with a contour ridge and the other without, are covered with straw mulch.*

*Figure 19. Plots from the 2010 Toth Quarry experiment on the effect of substrate type on moss establishment. Left: Plot on bare, flat limestone substrate. Right: Plot on limestone substrate covered with broken rocks of various sizes. Bricks mark the corner of subplots.*

## Statistical analyses

Depending on the experimental design used, a two-way, three-way or four-way analysis of variance with repeated measures was used to test the effects of substrate, topography, mulch and species on the change in moss cover over time. The repeated factor was the time of measurement.

*Figure 20. Cut-out plastic sampling frame. Umbrellas were used to evenly shade the plots when taking pictures, for better results.*

# 3 Main Findings and Comparisons with Other Studies

*Figure 21. Four-year old moss colonies established on a bare limestone experimental plot at Lawless Quarry.*

## Alvar mosses can be established on limestone quarry floors

Results from field experiments clearly demonstrate that alvar moss colonies can establish and grow on limestone quarry floors when proper introduction techniques are used.

When moss propagules were covered with straw mulch and introduced and on a flat limestone substrate or on thin soil, they established successfully at all sites and in all years. Not only did mosses successfully establish in the first year but they thrived. Unless disturbed, the newly established mosses continued to densify and expand laterally. Within three to four years, they developed into well-formed, stable, natural-looking colonies (Figure 21, 22, 26).

All species tested established successfully to some extent, but colony development was slower in some species than in others.

*T. tortuos*a established faster than the other species tested and reached nearly full cover within two to three years on mulched plots (Figure 22 and 23). In experiments monitored over longer periods, percent cover of slower-establishing species such as *S. rivulare* continued to increase over the years to reach levels comparable to that of *T. tortuosa* (Figure 23).

*E. procera*, a species that is not often found in depleted quarries, was able to establish when introduced on bare limestone and on thin mineral soil in depleted quarries (Figure 24).

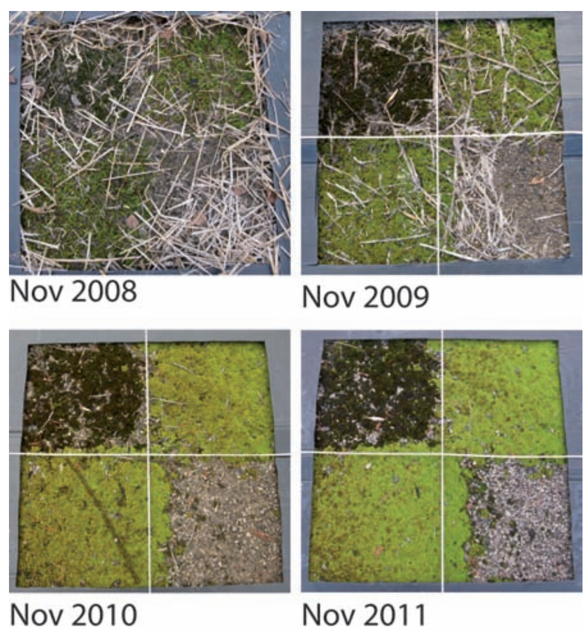


*Figure 22. Evolution of moss cover on a mulched plot over four years at Lawless Quarry. The pale green moss is T. tortuosa. The darker green moss is S. rivulare. The bottom right quadrant did not receive any moss. Straw mulch was gently removed prior to taking pictures and replaced afterward. Hardly any straw was left by the end of the third year.*

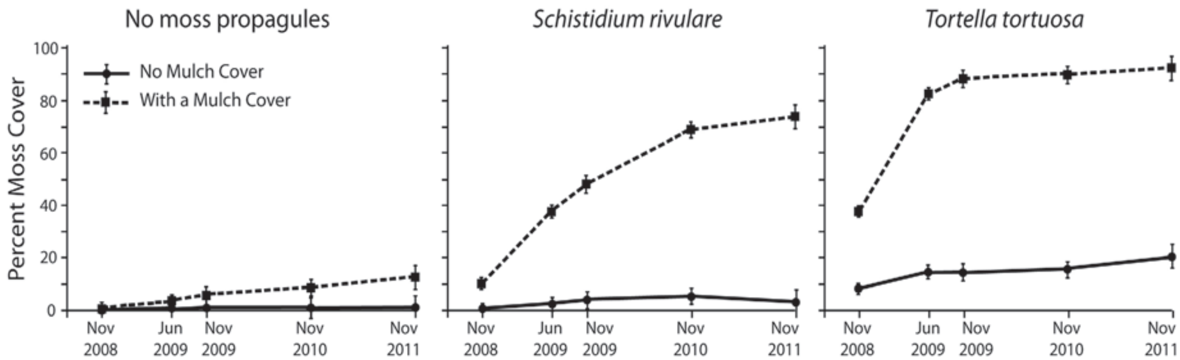


*Figure 23. Effect of mulching and propagule introduction on moss establishment over a three-year period at Lawless Quarry (Mean ± SE).*

Early experiments included plots where moss propagules were not introduced but otherwise treated the same way as plots where mosses were introduced (e.g. mulched, located on thin soil or with contour ridges). On these plots, moss establishment only occured at the edges where moss colonies located in adjacent quadrants sometimes expanded into the empty one (Figure 22 and 23). This result indicates that moss establishment from naturally occurring propagules cannot be triggered over the short term by changing environmental conditions alone.

All species tested in this study are early successional rocky alvar habitat species and are most suited for the initial stages of rehabilitating quarry floors. Alvar species that are found further along the gradients of soil depth, moisture and shade are even more likely to require site manipulation such as soil addition, mulching or the presence of sheltering vascular plants for establishment.

## The importance of a mulch cover

One single technique clearly stands out as being determinant to ensure moss establishment in depleted quarries: the use of straw mulch to cover and protect moss propagules after their introduction on limestone pavement (Figure 23, 24 and 25).

This result was found to be repeatable over the seasons, years and sites. Indeed, in nearly all experiments where we compared mulched to non-mulched plots, moss establishment was far more successful when a mulch cover was provided. Moss establishment was poor or absent on all non-mulched plots and, when some initial establishment took place, moss cover failed to increase over time.

The only trial where straw mulch failed to have a positive effect on establishment was when mosses were introduced on an irregular substrate composed of crushed rocks of various sizes (Figure 18 and 31). Observations suggest that this was due to pieces of straw and other debris accumulating on top of the mosses that established in cracks between rocks, which resulted in smothering the developing propagules.

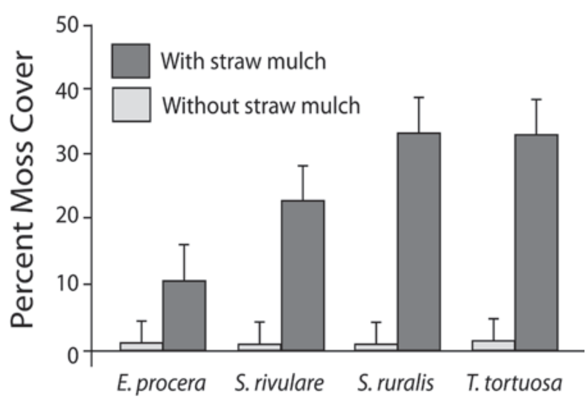


*Figure 24. Effect of mulching on the establishment of four species of moss after one growing season at Flecher Creek Quarry (Mean ± SE).*


*Figure 25. Moss establishment after three years on plots initially covered with mulch compared to plots that were not. Lawless Quarry, June 2008 experiment. Images taken in November 2011. Left: bare rock substrate; Right: bare rock covered with a thin layer of soil. The pale green moss is T. tortuosa. S. rivulare is the darker green one.*

The presence of straw mulch is only critical in the early stages of development of moss colonies. After two or three years, when most of the straw had disappeared through decomposition, the newly established moss colonies continued to grow and remained healthy (Figure 22, 25 and 26).

Covering propagules with straw mulch has also been shown to be of utmost importance for the establishment of sphagnum mosses on bare peat, and is a key element in successful peatland restoration (Rochefort et al. 2003; Quinty and Rochefort 2003).

On bare peat, straw mulch was shown to increase the humidity of the air layer just above the surface and to reduce evaporative water loss and substrate temperature, both by shading the surface and by reflecting incoming light due to the straw high albedo (Price et al. 1998).

The overall effect of mulch in peatland restoration is therefore to create a more favorable environment at the substrate-air interface where moss propagules are located. Similar factors are likely at play when straw mulch is applied over moss propagules that are introduced on the bare limestone floor of a quarry.

*Figure 26. View of an experiment conducted at Lawless Quarry at its outset in June 2008 (left) and three years later in fall 2011(right). The well established moss colonies that can be seen on the picture to the right developed on plots that were initially covered with straw mulch. Unmulched plots harboured almost no moss. When some moss establishment occurred in the absence of mulch, it was on plots located on thin soil.*

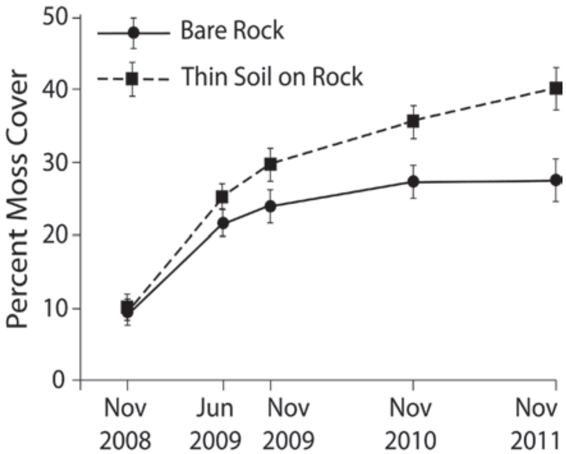


*Figure 27. Effect of substrate type on the establishment of mosses on a quarry floor at Lawless Quarry (Mean ± SE).*

## Substrate and amendments

The presence of an existing thin soil layer composed of sand, gravel and fines on the quarry floor enhanced moss establishment (Figure 27).

This thin mineral and organic layer may help in two ways:

1. by keeping moss fragments in place during early establishment despite wind and rain;
2. by storing water that keeps fragments moist longer after a rain event.

Interestingly, in terms of restoration techniques, it is possible to mimic the positive effect of a naturally occurring layer of thin soil by covering bare limestone with a few millimeters of sand or of a mixture of sand and peat. Indeed, results showed that adding a thin layer of amendment on bare rock prior to moss introduction had an effect similar to the presence of naturally occurring mineral soil: moss establishment was significantly improved on amended plots (Figure 28). No significant difference could be detected between sand-treated and sand and peat-treated plots, although moss cover was slightly better on the later.

It is important to note that, even if significant, the positive effect of adding a thin layer of soil is never as substantial as the striking, positive effect associated with the use of straw mulch.

Larson et al. (2006) showed that, although not essential, the addition of a thin layer of sand and organic matter may improve the establishment of alvar vascular plants seeded in quarries.

## Microtopography

The presence of a sheltering contour ridge had very little impact on moss establishment and did not compare to the significant positive effect of straw mulch (Figures 29 and 30).

In plots with contour ridges but without mulch, moss propagules were displaced over time and tended to aggregate along the ridges (Figure 29). Yet moss establishment in this treatment, even when considering these displaced propagules, was low in comparison to that in plots with straw mulch.

Results also showed that moss establishment on a substrate composed of rocks of various size was not better than on flat limestone (Figure 31). This result was unexpected and is somewhat counter-intuitive as,

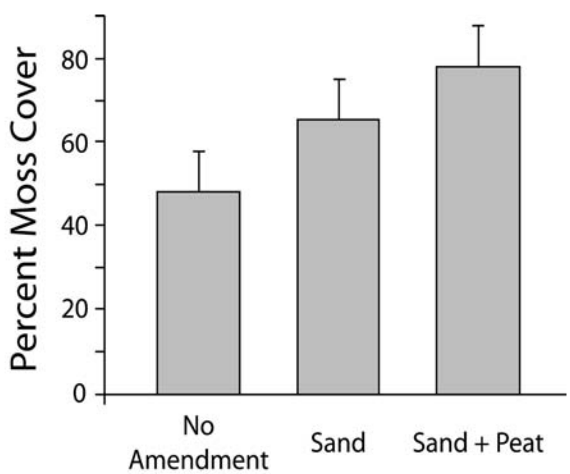


*Figure 28. Effect of the addition of a thin layer of amendments over a bare limestone substrate prior to moss introduction at Lawless Quarry (Mean ± SE, first and second year data pooled).*


*Figure 29. View of the effect of a sheltering rock ridge on moss establishment. Lawless Quarry, Images at the end of the third year. One of the plots (with three subplots) is on bare rock (left), the second is on thin mineral soil (right). Presence of an initial mulch cover is indicated. No mulch remained after three years. One half of each subplot received T. tortuosa (pale green). The second half received S. ruralis (darker green).*

in old quarries, mosses are often found in cracks or in areas with small rocks and pebbles (Figure 32).

In peatland restoration, increasing the topography of a site by harrowing or ploughing does not improve sphagnum moss establishment when compared to flat areas (Price et al. 1998). These authors showed that the gains observed in the lower elements of the topography did not compensate for the losses incurred in higher zones, resulting in an overall reduced moisture level for the site. Similar phenomena may explain the poor establishment success of mosses on a broken limestone substrate.

Stabler (2009) showed that increasing the spatial heterogeneity of the rock pavement improves the establishment of alvar plants on quarry floors. Regardless of the way in which alvar vascular species were introduced–seeds or plugs–plots with manufactured heterogeneity or microtopography supported a more diverse and productive plant communities that had better survival rates compared with plots where no changes were made to the bedrock.

In this regard, mosses seem to respond differently than vascular plants to changes made to the microtopography of a quarry floor.

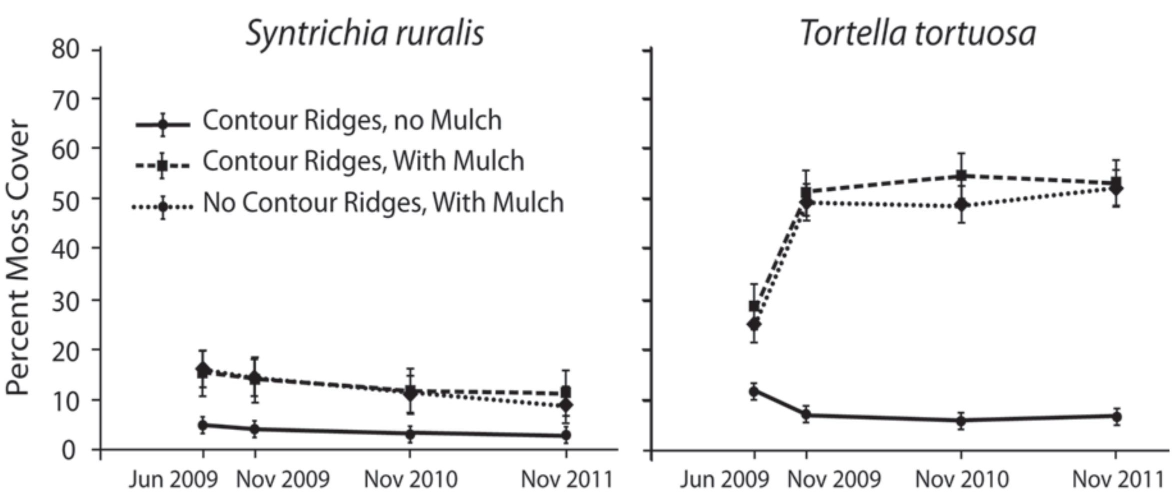


*Figure 30. Effect of a sheltering topography (low contour ridges made of small rocks) on the establishment of two species of moss introduced on a quarry floor at Lawless Quarry, and comparison to the effect of straw mulch (Mean ± SE).*

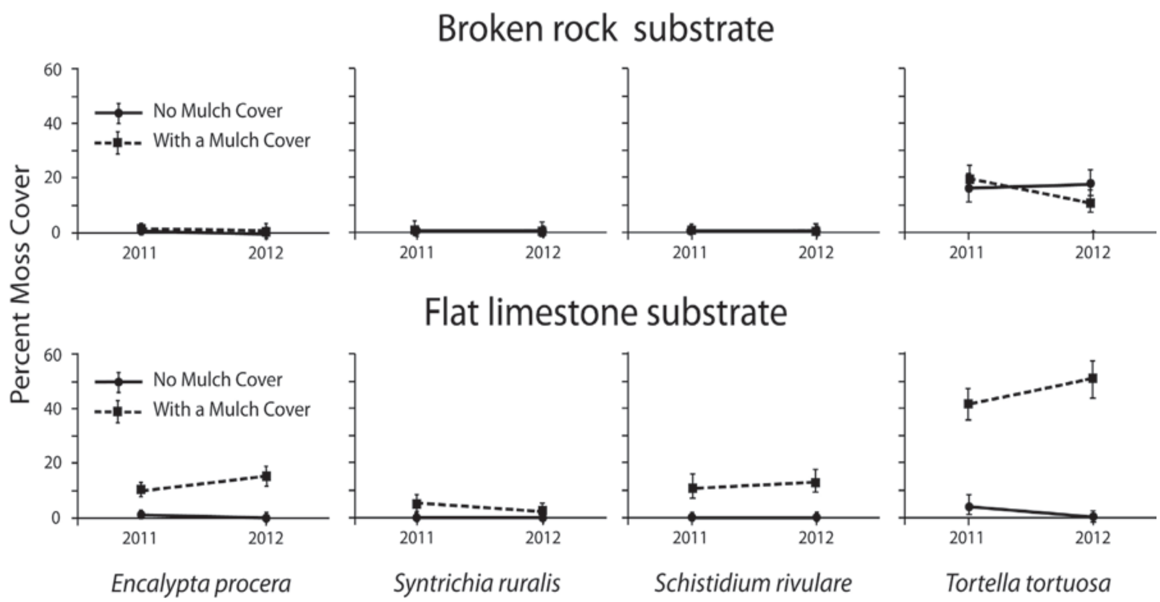


*Figure 31. Effect of mulch cover and species on moss establishement on a flat limestone substrate and on a substrate composed of rocks of various sizes (Toth Quarry, backtransformed mean ± SE).*

## Flooding disturbances

Flooding was not among the factors originally planned for study during this project. However, observations showed that this factor might be very important to consider in quarry restoration, as a number of our experimental plots were affected or even destroyed by flooding (Figure 33, 34 and 35). Even very shallow flooding (sheet flooding) or infrequent flooding events following hard rains were sufficient to displace propagules and hinder moss establishment.

Flooding was not considered in the Tomlinson et al. (2008) study of abiotic factors that determine plant community structure in quarries and alvars. From our experience, areas vulnerable to flooding are difficult to determine without a number of regular visits to a site, and flooding varies from year to year depending on precipitation. Yet, observations made on several old quarries suggest that flooding may play a very significant role in determining which areas of the quarry floor are favourable or unfavourable to the establishment of mosses and, most likely, of other plants as well.

Potential for water movements and pooling of excess water therefore need to be taken into account in quarry restoration.

*Figure 32. The weathered floor of an old quarry with mosses growing in the cracks and among pebbles on the limestone pavement.*


*Figure 33. Location of the plots that were lost to flooding at Hendry Quarry. (A) Image taken in the fall of 2008, when all plots were still in place. (B) Image taken in early March 2009, showing the extent of water and ice in the southeast corner of the quarry. Blue arrows indicate plots that were completely washed away. Yellow arrows indicate plots where at least some mosses and mulch remained.*

*Figure 34. An inundated plot at Toth Quarry, in an area located at the base of the reworked quarry wall.*

*Figure 35. Some of the experimental plots at Lawless Quarry (to the right) were washed out by heavy rains in the fall of their second year.*

# 4 Conclusions and Recommendations

*Figure 36. Common Garter Snake on the bare limestone floor of Lawless Quarry, October 2008.*

## Potential for quarry rehabilitation

This project demonstrated that the establishment of alvar mosses in depleted quarries can be accomplished using techniques that are relatively simple and inexpensive. Moss introduction, either on a thin soil layer or directly on a bare limestone floor, followed by the application of straw mulch was shown to be sufficient to ensure moss establishment on limestone pavement in areas where the developing moss colonies were safe from flooding.

Conditions required for moss establishment on bare limestone are generally compatible with the techniques recommended by Larson et al. (2006) for the establishment of alvar vascular plants in quarries. Soil amendments suggested for vascular plants are compatible with the requirements of mosses. Like alvar vascular plants, alvar mosses do not need fertilization to establish. Only in their response to substrate heterogeneity do moss and vascular plants seem to differ from each other with regards to quarry restoration.

## Species of mosses to use

Common alvars species that prefer early successional 'rocky' habitat, regardless of whether the site is alvar or quarry, are the most suited for the initial stages of rehabilitating quarry floors. Such species, especially *T. tortuosa* but also *S. ruralis* and *S. rivulare,* are recommended for bare open sites. In areas where vegetation is already present, later successional alvar species could also be used. The Final Report of this project provides more information on the distribution of various alvar and quarry species in function of habitat (Campeau 2013).

## Moss sourcing and preparation

The availability and sourcing of native species propagules appropriate for the task at hand is an important issue to consider in quarry restoration.

Technically, mosses are generally easy to collect as most are only loosely attached to the substrate. As the quantities needed for this research project were small, mosses were picked by hand. At a somewhat larger scale, they could also be collected using simple tools such as a shovel or a rake. For this project, the collected moss colonies were broken apart by hand into a mixture of individual stems, clumps of a few stems and fragments. For larger quantities, equipment could likely be adapted to attain a similar result. After collection and preparation, propagules should be kept in a cool shaded area and spread without delay.

For comparison, in large-scale peatland restoration operations, the sphagnum moss layer and other surface vegetation of a donor site is shredded to a shallow depth using an agricultural rotovator prior to collection (Quinty and Rochefort 2003). The resulting material is composed of loose fragments a few centimeters long and of small chunks. This material is then placed in windrow and / or picked up using various type of machinery (e.g. front end loader, modified clamshell bucket).

One major difference should be pointed at when comparing the sourcing of mosses for peatland restoration and their sourcing for quarry restoration: the likelihood of finding large areas where targeted moss species could be collected from.

Alvars are valuable ecosystems that are found only sporadically within the Ontario landscape. Harvesting mosses from pristine alvars for quarry restoration is therefore not a viable or environmentally acceptable option. Many species recommended here for establishment on limestone pavement can be found not only in alvars but also in old quarries. Such quarries may be more appropriate choices for donor sites in term of ecological conservation but, in general, the surface covered by mosses in old quarries is very limited. Another option would be to salvage mosses—if present—from an area to be quarried in the near future and use these mosses to restore a depleted quarry. In all likelihood, this option would have only limited application, especially with regards to geography and timeliness of operations.

The availability of propagules to restore alvar plant communities is a concern that is not limited to mosses. Larson et al. (2006) recommended that alvar plants be grown in nurseries in order to provide seeds for quarry restoration. Likewise, mosses used for restoration should ideally be propagated and grown for that purpose.

A first avenue to achieve this goal would be to dedicate an old quarry to the purpose of establishing a semi-managed nursery where mosses would be introduced using the techniques suggested here and left to grow naturally. After a few years, the newly established colonies would be harvested and used as sources of propagules for quarry restoration projects elsewhere.

Another option is to purchase propagules from a nursery that commercially grow mosses on a large scale. Bryophyta Technologies operates such a specialty nursery in partnership with a major Quebec plant grower and, on special order and with sufficient advance notice, could provide Ontario practitioners with an adequate supply of mosses appropriate for quarry restoration.

Bryophyta Technologies also has the expertise to help plan and establish a semi-managed propagation area in an old quarry if this option is preferred.

## Site preparation and planning

A first step in planning moss introduction in a depleted quarry is to identify and delineate areas that are prone to flooding. Moss introductions are at risk to fail in areas that may be flooded, even temporarily. Practitioners should therefore plan for the redirection of excess water in order to avoid damage caused by shallow surface flooding. Meeting this requirement may be transformed into an opportunity to increase site heterogeneity and biodiversity by creating areas where water pools temporarily or permanently, thus providing habitat for a variety of plants and fauna that would not otherwise colonize the site (Figure 37). Seek advice from hydrologists at the planning stage on this aspect.

A second step is to delineate areas already covered with vegetation or soil and those on bare rock. Existing soil and vegetation should be left in place as they may help moss establishment. Adding a thin layer of mineral or organic material on bare limestone may favour moss establishment, but is not necessary.

Although increasing surface heterogeneity of a site by adding rock debris may be beneficial for vascular plants (Larson et al. 2006; Stabler 2009), results from the current study suggest that this action can be detrimental to mosses. An option to accommodate the needs of all plant groups would be to create a heterogeneous site where areas of flat limestone are interspersed with areas covered by thin soil, rock ridges or shallow depressions, leaving patches of

*Figure 37. The pond and walls of Lawless Quarry provide habitat opportunities for increased biodiversity.*

existing soil and vegetation in place. Each of these features could then be seeded or inoculated with species that are best adapted to local conditions. Areas of bare rock could be dedicated to moss colonization, along with seeds of vascular plants that are well suited to bare rock and extremely shallow soil. Areas of crushed rocks, low rock ridges, cracks or shallow soils may receive seed and plugs of alvar shrubs and forbs. Young trees or tree seedlings could be introduced in areas with deeper soils or in cracks.

## Moss introduction

Moss introduction can be done either in the spring, early summer or fall. To ensure rapid establishment, propagules should be introduced to the area to be restored at a density ratio of approximately 1:10 to 1:15. In other words, one square meter of mosses, once broken into pieces (propagules) is sufficient to treat ten to fifteen square meters of quarry floor.

For this project, mosses were spread by hand as experimental plots were small. In peatland restoration, a tractor and manure spreader is used to spread moss propagules over large areas (Quinty and Rochefort 2003). Similar or smaller equipment could likely be used for larger-scale quarry restoration operations.

## Mulching

Mulch cover should be thin enough to let some light reach the moss propagules, while still providing enough structure to create an air layer immediately above the rock surface where temperature and moisture conditions will be more favorable to the plants. Straw with long unbroken stems gives better results than straw that has been chopped or flattened by harvesting equipment. Wheat and spelt straw often offer the needed qualities, but other types of straw will work as well.

Mulch should block approximately 60% of the incident light and moss propagules should be barely visible among the straw strands. If the straw layer is too thick, it will impede moss establishment. If it is not sufficiently dense, it will not provide enough protection to the developing propagules.

In this project, straw was spread on plots by hand. Mechanized alternatives for spreading straw exist and have been used for large-scale peatland restoration operations (Quinty and Rochefort 2003).

## Additional suggestions

Unfortunately, restoration projects are oftentimes not sufficiently documented, making the evaluation of new techniques and the exchange of information between practitioners less effective.

Practitioners should record restoration operations using drawings, written protocols, notes and before and after photos. Ideally, vegetation establishment should be monitored over time to keep track of successes and failures and to communicate results to other professionals, property owners, quarry operators and to the general public.

They should also ensure, as much as possible, that the establishing vegetation is protected from disturbance by trespassers (e.g.using fences or signage) and that restored areas will be protected in the long run.

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# 6 Acknowledgments


*Figure 39. Northern Green Frog in a pond at Fletcher Creek Quarry.*

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*Figure 40. Syntrichia ruralis, a moss found both in alvars and in quarries.*

bryophyta