Establishing Alvar Mosses on Quarry Floors:

A Necessary Step in the Restoration of Quarries to Alvars

Four-year old moss colonies established on a bare limestone experimental plot.

Final Report

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FINAL REPORT

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Contents

1 Executive Summary

Figure 1-1. Four-year old moss colonies established on an experimental plot at Lawless Quarry.

Objectives and Approach

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

The research was intented 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.

The approach used in this project combined:

1. Analyses of already existing quarry and alvar vegetation survey data to help us 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. Several species of mosses were used.

Three main environmental factors that may affect moss establishment were examined: the type of substrate, the use of a protective straw mulch cover and changes in microtopography made in order to create a sheltered environment for mosses.

Most experiments included more than one environmental factor and two or more species, and all were monitored for more than one year. This allowed us to explore interactions between species, environmental factors and time.

Results

Analysis of existing survey data

Analyses of previous survey data suggested that species that grow in conditions common to parts of both alvars and quarry floors–*S. rivulare* and *T. tortuosa* for example–are the most suited for the initial stages of rehabilitating quarry floors. These species were given priority in our field experiments. Analyses also suggested that soil depth, moisture and degree of exposure are important and potentially modifiable factors that determines the distribution of moss species in alvars and quarries. These factors were given priority for field experimentation.

Figure 1-2. Three year moss establishment on a plot at Hendry Quarry.

Field experiments

Results from field experiments clearly demonstrate that when using proper restoration techniques, alvar moss colonies can establish and grow on limestone quarry floors.

Not only were the new moss colonies successfully established at all our four sites but they thrived. Unless disturbed by flooding or by humans, colonies continued to densify andexpand laterally over years. All species we tested were successful in one trial or another, although colony development was found to be slower in some species than in others.

One single technique clearly stands out as being determinant to ensure moss establishment success in depleted quarries: the use of straw mulch to cover and protect moss propagules after their introduction on bare limestone pavement. The positive effect of straw mulch was observed in a number of experiments and was repeatable over the seasons, years and sites.

Experiments showed that plots located on an existing thin layer composed of sand, gravel and fines had better moss establishment success than plots located on bare limestone. Our experiments also demonstrated that is it possible to mimic the positive effect of a naturally occurring layer of thin soil by covering bare limestone with a few millimetres of sand or of sand mixed with peat.

Using low rock ridges to shelter propagules did not improve moss establishment and could not replace the use of mulch. Moss establishment was not enhanced on a substrate composed of rocks of various size, and especially not on mulched plots.

Flooding was not among the factors we had planned to study during this project. However, our observations showed that this factor may be very important to consider in quarry restoration. Even very shallow flooding (sheet flooding) or infrequent flooding events following hard rains were sufficient to displace propagules and hinder moss establishment. Potential for water movements and pooling of excess water therefore need to be taken into account in quarry restoration.

Conclusions and Recommendations

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

Conditions required for moss establishment on bare limestone were found to be compatible with the techniques recommended by Larson et al. (2006) for the establishment of alvar vascular plants in quarries.

As for vascular plants seeds, the availability of moss propagules is an important issue to consider in quarry restoration. Collecting propagules from the wild may prove difficult and even controversial. A better option may be to propagated selected species of mosses in a specially managed area such as an old quarry dedicated to this purpose or to purchase them from a specialized plant nursery.

2 Project Overview

Background

Limestone quarry floors present a number of challenges to revegetation, including very shallow or non-existent soils and harsh environmental conditions. Starting in 2003, 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, which are naturally occurring limestone pavement ecosystems of significant conservation value.

Figure 2-1. An alvar on the Bruce Peninsula, Ontario.

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). Despite the low plant biomass, the vascular plant flora of Ontario alvars is highly diverse, and contains some unusual, rare and even endangered native species (Catling and Brownell, 1995; Schaefer, 1996 and reference therein).

Surveys conducted by University of Guelph researchers showed that quarry floors resemble alvars with respect to many environmental conditions, and that a number of plants characteristic of alvars are also present in old quarries (Tomlinson et al., 2008). These authors concluded that old quarry floors and alvars are sufficiently similar to justify the use of alvars as a restoration target for abandoned quarries. The same researchers also showed that a number of alvar vascular plant species can be established in quarries by the addition of seeds and simple soil amendments.

The advantages of restoring depleted quarries to alvars are two-fold. First, rehabilitated quarry floors have the potential for becoming habitat extensions for alvar species. Second, the development of a simple but effective methodology to rehabilitate alvar communities on limestone quarries may reduce the need for costly rehabilitation alternatives such as the importation and placement of large quantities of topsoil, while still resulting in the restoration of a valuable natural habitat. The end results would be an inexpensive method to rehabilitate depleted sites for the Management of Abandoned Aggregate Properties (MAAP) program and quarry operators as well as an extension of available habitat for alvar species.

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 research team to be the least successful at re-establishing on their own on abandoned quarry floors (Tomlinson et al. 2008).

Out of the 283 species recorded in the Bruce Peninsula alvar study, Schaefer (1996) 63% were vascular plants, 19% were lichens and 18% (50 species) were bryophytes. In comparison, out of the 246 species found on quarry floors, 81% were vascular plants, 13% were lichens and a mere 6% (14 species) were bryophytes (Tomlinson et al. 2008). The resemblance observed between quarry floor and alvar flora was much higher for vascular plants than for lichens and bryophytes, with 36% species in common between both habitats for vascular plants compared to 11% and 12% for lichens and bryophytes respectively. Overall, the percentage cover occupied by bryophytes on quarry floors was lower than that occupied by them on alvars and in 4 out of 13 quarries, no bryophytes at all were recorded on the surveyed plots.

Yet, 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. Bryophytes are known as pioneer species that can establish on very poor, bare mineral surfaces and rock pavement. Once established, 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 vascular plants establishment and survival.

Figure 2-2. An old quarry with a fair amount of vegetation growing at the base of the walls and along the margins of a lower level pool.

Figure 2-3. Mosses, low shrubs and stunted trees of an alvar of the Bruce Peninsula, Ontario.

Consequently, establishing bryophyte communities on limestone pavement is likely a very important component in the successful restoration of quarry floors to alvars.

Project Objectives

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

The research was intented 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 (Presented in Chapter 3 of this report);
2. A series of field experiments on how to establish alvar mosses on limestone quarry floors (Presented in Chapter 4 of this report).

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.

Figure 2-4. Tortella tortuosa, a moss that is found on limestone both in alvars and in quarries. Here growing near the base of a wall of the quarry pictured in Figure 2-2.

Most experiments included more than one environmental factor, two or more moss species and all were monitored for more than one year. This allowed us to explore interactions between species, environmental factors and time.

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).

Project Timeline

The project was accepted for funding in January 2008. The work began shortly after with an analysis of previous moss survey data that was conducted by University of Guelph researcher Dr. Uta Matthes. This analysis was completed by June 2008.

Screening for potential experimental sites was done in spiing 2008 in collaboration with MAAP program staff., followed by field visits and contacts with landowners in summer 2008 that allowed us to select the quarries we would be working on and get permission for access.

The first field experiment was initiated in south-eastern Ontario in June 2008, followed by more experiments in the same region in August 2008, October 2008 and October 2009. Additional experiments were initiated in 2010 in quarries south-west of Toronto. Data on the different experiments were collected each fall from 2008 to 2012.

Figure 2-5. The weathered floor of an old quarry, with vegetation growing in the cracks of the limestone pavement.

Communication of Results

Early results of the project were presented at the Canadian Land Reclamation Association (CLRA) Conference in Québec City in August 2009. A poster presentation, co-authored by Uta Matthes and Suzanne Campeau and entitled *The Use of Community Ordination in the Establishment of Restoration Protocols,* described the approach used to select the species for the experiments. The second presentation, a talk presented by Suzanne Campeau and entitled *Establishing Alvar Mosses on Limestone Quarry Floors in Ontario*, focused on field experiments. A paper authored by Matthes and Campeau is published in the *Conference Proceedings*. The abstract of the second paper is also published in the Proceedings.

An article targeting the general public was printed in *Quatre-temps,* a tri-monthly magazine published by the *Société des amis du Jardin botanique de Montréal*. It was part of the magazine special issue on bryophytes. The article, entitled *Les mousses et la végétalisation de sites perturbés* talks about rehabilitation research conducted with mosses in general but pay a particular attention to the current MAAP program funded research project on alvar mosses. A similar, but somewhat more technical paper that focus specifically on the present project has been printed in the Spring 2012 issue of *Canadian Reclamation,* a magazine published by the CLRA.

Figure 2-6. The nearly bare floor and walls of a quarry where extraction activities ceased more than fifty years ago.

A scientific paper detailing the major experiments and findings of the project will be submitted shortly to *Ecological Restoration,* a peer-reviewed journal published by the Society for Ecological Restoration. Final results of the project will also be presented in a talk that will be given at the 2014 Annual Meeting and Conference hosted by the Quebec Chapter of the CLRA.

Six progress reports were presented to the MAAP program during the course of the project in addition to this *Final Report*. A *Summary Report* suitable for circulation to licensees and permittees in the aggregate industry was also produced.

3 Analysis of Existing Survey Data

Authorship

These analyses used data that were collected by graduate students Shannon Tomlinson and Claudia Schaefer, both working under the direction of Dr. Doug Larson at the University of Guelph. With the researchers permission, we extracted the information pertaining to bryophytes from these larger vegetation datasets in order to run statistical analyses on this component alone. The analyses and interpretation of data were conducted by Dr. Uta Matthes at the University of Guelph.

Introduction

Selection of a suitable restoration target ideally involves collection of comparative species and environmental data from both the site requiring restoration and the potential target ecosystem. Tomlinson et al. (2008) measured the biophysical conditions of abandoned limestone quarry floors and compared them to data collected previously from natural alvars (Schaefer and Larson 1997). The results showed that quarry floors resembled alvars with respect to many environmental conditions and that some plant species characteristic of alvars had already established naturally in old quarries. This confirmed alvars as a suitable restoration target for abandoned limestone quarry floors.

Although bryophytes are an important component of alvar vegetation in terms of both biodiversity and the role they play at the ecosystem level (Schaefer and Larson 1997), they appear to be less successful than other taxonomic groups in establishing on their own on abandoned quarry floors (see Section 2 of this report). This makes it necessary to develop techniques specifically for the reintroduction of bryophytes to abandoned quarries.

Figure 3-1. Type of sampling quadrat used in C. Schaefer and S. Tomlinson studies, here pictured on an alvar. Photo by J.A. Gerrath.

Having identified a suitable restoration target, practitioners are faced with two questions when devising restoration protocols. The first is how to select the species most suitable for restoration purposes from among the many present at the target site. If site remediation is being considered before introducing species, the second question is which habitat factors should be manipulated in order to maximize restoration success. We here use multivariate community ordination to help answer these questions for the establishment of alvar bryophytes on abandoned limestone quarry floors

Methods

Datasets

We used previously published data from 7 natural alvars (Schaefer and Larson 1997) and 9 abandoned limestone quarries of various ages (Tomlinson et al. 2008) in southern Ontario. The combined data set contained bryophyte species frequencies and 7 environmental variables (percent cover of woody debris, litter, bare rock, soil, and lichens, as well as minimum and maximum soil depth) for a total of 305 plots. Eight additional soil nutrient variables were available for a subset of 72 of these plots (plant-available phosphorus, potassium, calcium, magnesium, ammonium, nitrate, organic matter, and pH). All analyses were performed in parallel on the large data set and the subset. The quarry floors supported a total of 14 bryophyte species while alvars contained 50 bryophytes, with 6 species in common between both habitats (Tomlinson et al. 2008).

At the onset of the current project and with the permission of the researchers who own the data, we extracted the information pertaining to mosses from these two large datasets in order to run statistical analyses on the bryophytes alone and determine how species distribution was controlled by the abiotic environment in both habitats.

Figure 3-2. One of the quarries surveyed during S. Tomlinson study.

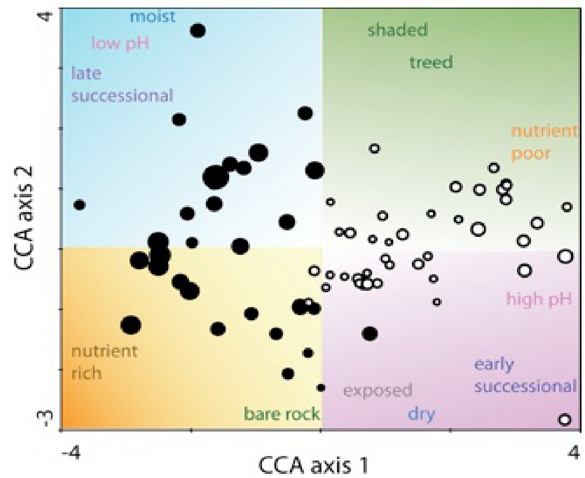

Figure 3-3. Ordination diagram showing axis 1 vs axis 2 of CCA. Black circles represent alvar plots, white circles represent quarry plots; size of the circle represents bryophyte species richness. Reprinted from Matthes and Campeau, in press.

Stastistical analyses

Multivariate ordinations were performed on the combined quarry floor and alvar data to determine how bryophyte species distribution was controlled by the abiotic environment in both habitats.

For both the full set and the subset of quarry floor quadrats, detrended correspondence analysis (DCA) was performed first to reveal patterns of bryophyte community structure present in the data set. DCA arranges both samples and species along ordination axes representing hypothetical environmental gradients controlling species composition (ter Braak and Šmilauer 2002). The species data were subsequently used in conjunction with the environmental data in a canonical correspondence analysis (CCA) to determine relationships between the patterns of species composition and the measured environmental variables. CCA additionally incorporates and focuses on the effects of the measured environmental variables on species composition.

The DCA and CCA analyses were interpreted jointly to reveal:

1. the most important environmental controls of species composition at the sites;
2. the differences and similarities in the environment of the degraded and target sites, and the degree to which environmental conditions overlapped between habitats; and
3. the environmental preferences of individual bryophyte species to select candidates for use in restoration.

Ordinations were performed using the CANOCO software v. 4.5 (ter Braak and Šmilauer 2002).

Results

The distribution of samples and species in the DCA ordination diagrams was very similar for the full data set and the subset, indicating that the species-environment relationships were well represented

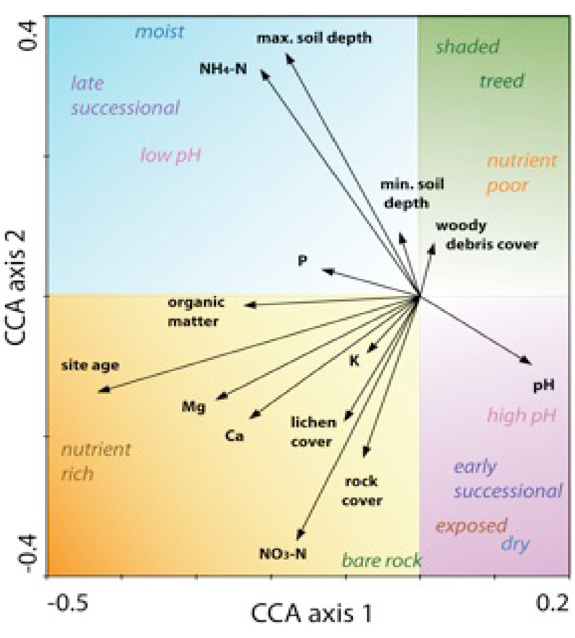

Figure 3-4. Environmental ordination diagram, where measured environmental variables are shown as vectors in ordination space. Reprinted from Matthes and Campeau, in press.

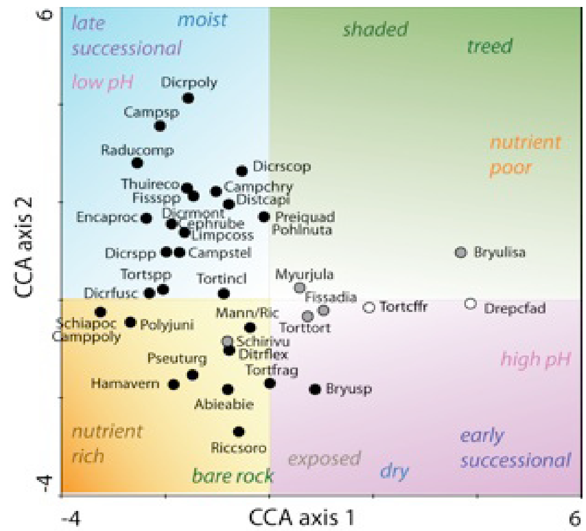

Figure 3-5. Species ordination diagram, where each symbol represents a bryophyte species. Species present only in alvar plots are represented by black symbols; only quarry plots, white symbols; and both, grey symbols. For species abbreviations see Table 1. Reprinted from Matthes and Campeau., in press.

by the smaller data set. Since the subset contained additional environmental variables, only the results from the subset are reported here. Likewise, the placement of samples and species along the first two axes of the CCA was not drastically different from that of the DCA. We will therefore focus on the CCA in interpreting the results.

Because of the large discrepancy in the ages of quarries vs. alvars, we were initially concerned that including ‘site age’ as an environmental variable might artificially inflate the differences between quarries and alvars. We therefore performed two versions of the CCA, one with site age included and one without it. As it turned out, the two ordinations were scarcely different, probably because the effect of site age was adequately represented by that of the combined soil nutrient variables. We therefore present the original analysis that includes site age.

The results show the bryophyte community of alvars and quarry floors being organized along two major environmental gradients (Figures 3-3 and 3-4). The primary (or strongest) gradient, represented by the horizontal axis, separates alvar plots from quarry plots with a small amount of overlap. The secondary gradient, represented by the vertical axis, is present within both habitat types, although alvars have greater variability along this gradient than do quarry floors (Figure 3-3).

The gradients represented by the axes are composites of multiple environmental factors, whose vectors in ordination space are shown in Figure 3-4. The diagonal from bottom right to top left in the diagrams can be best described as a 'successional' gradient in terms of soil and vegetation development. It separates quarry plots from the majority of alvar plots and is associated with an increase in bryophyte richness (Figure 3-3). A large variety of later-successional taxa, for example *Polytrichum*, are found at the top left of the corresponding species ordination diagram (Figure 3-5), while only a few early-successional taxa such as *Bryum* are found at the bottom right. It is important to note that this 'successional' gradient is largely independent of the chronological age of the sites, which increases from right to left in the diagrams. The 'successional' gradient is also not equal to a nutrient gradient. While on average alvar plots have higher levels of most nutrients than quarry plots, plots with low and high bryophyte richness are both distributed over a wide range of nutrient levels.

Discussion

As already shown by Stark et al. (2004), alvar soils do not necessarily develop over time: whether soil and vegetation will develop or open pavement will persist is entirely controlled by the microenvironment.

These results have interesting implications for quarry rehabilitation. While many alvar bryophytes prefer conditions that are currently not met on quarry floors (those represented by the upper left quadrant in Figure 3-3 to 3-5), there are a number of species that grow in conditions common to parts of both alvars and quarry floors (the bottom and center of Figures 3-3 to 3-5). It is these species – for example, *Schistidium rivulare* or *Tortella tortuosa* - that we conclude are most suited for the initial stages of rehabilitating quarry floors since they 'bridge' the conversion of quarry to alvar and are likely to establish without extensive site modifications. These species have similar habitat preferences : early successional 'rocky' habitat, regardless of the age of the site and regardles of whether the site is alvar or quarry. Alvar species distant from the zone of overlap (e.g. *Dicranum polysetum* or *Campylium* sp.) are unsuitable for early stages of rehabilitation but may be used at later stages or require some site manipulations in order to be successfully established.

What changes could be made to the quarry floor environment to allow a greater variety of alvar mosses to grow? The results showed that the bryophyte communities of quarry floors and alvars were differentiated by a primary gradient roughly corresponding to 'successional stage' (in terms of soil development, not chronological age). Soil depth, moisture and degree of exposure were important and potentially modifiable factors correlated with this gradient. For exemple, sand or compost could be used to make the quarry substrate more similar to alvar soil (Stark et al. 2004). The slow, natural progression of soil development in suitable microsites could be accelerated by the addition of soil or mulch. Likewise, mulching would increase surface shade and retain moisture, with the effects of shifting conditions more toward those represented by the top left in Figures 3-3 to 3-5. While nutrient gradients that controlled species composition were present within both habitat types, they do not seem to control species richness. Nutrient additions are therefore less likely to benefit alvar species establishment on quarry floors than the factors related to 'successional stage'. It is to be expected that successful bryophyte establishment on quarry floors will always be patchy, since as with alvars, the potential for 'successional' development will be constrained by microtopography.

Table 1. List of bryophyte species present in the data subset (72 plots) and their abbreviations used in Figure 2C. Species in bold were found only on quarry floors, underlined species were found in both habitats, and all others were present only on alvars.

Abie abie	= *Abietinella abietina* (Hedw.) Fleisch (syn. *Thuidium abietinum* (Hedw.) Schimp. in BSG)
<u>Bryu lisa</u>	= *Bryum lisae* var. *cuspidatum* (Bruch & Schimp. in BSG) Marg.
Bryu sp	= *Bryum* sp.
Camp chry	= *Campylium chrysophyllum* (Brid.) J. Lange
Camp poly	= *Campylium polygamum* (BSG) C. Jens
Camp stel	= *Campylium stellatum* (Hedw.) C. Jens.
Camp sp	= *Campylium* sp.
Ceph rube	= *Cephaloziella rubella* (Nees) Warnst.
Dicr fusc	= *Dicranum fuscescens* Turn.
Dicr mont	= *Dicranum montanum* Hedw.
Dicr poly	= *Dicranum polysetum* Sw.
Dicr scop	= *Dicranum scoparium* Hedw.
Dicr spp	= *Dicranum* sp.
Dist capi	= *Distichium capillaceum* (Hedw.) Bruch & Schimp. in BSG
Ditr flex	= *Ditrichum flexicaule* (Schwaegr.) Hampe
Drep cfad	= *Drepanocladus* cf. *aduncus*
Enca proc	= *Encalypta procer*a Bruch
<u>Fiss adia</u>	= *Fissidens adianthoides* Hedw.
Fiss spp	= *Fissidens* sp.
Hama vern	= *Hamatocaulis vernicosus* (Mitt.) Hedenas (syn. *Drepanocladus vernicosus* (Mitt.) Warnst.)
Limp coss	= *Limprictia cossonii* (Schimp.) Anders. et al. (syn. *Drepanocladus revolven*s var. *intermedia* (Lindb.) Grout)
Mann /Ric	= *Mannia fragrans* (Balbis) Frye & Clark or *Riccia sorocarpa* Bisch. (undifferentiated)
<u>Myur jula</u>	= *Myurella julacea* (Schwaegr.) BSG
Pohl nuta	= *Pohlia nutans* (Hedw.) Lindb.
Poly juni	= *Polytrichum juniperinum* Hedw.
Prei quad	= *Preissia quadrata* (Scop.) Nees
Pseu turg	= *Pseudocalliergon turgescens* (T. Jens.) Loeske (syn. *Scorpidium turgescen*s (T. Jens.) Loeske)
Radu comp	= *Radula complanata* (L.) Dum.
Ricc soro	= *Riccia sorocarpa* Bisch. (see also 'Mann/Ricc')
Schi apoc	= *Schistidium apocarpum* (Hedw.) Bruch & Schimp. in BSG (syn. *Grimmia apocarpa* Hedw.)
<u>Schi rivu</u>	= *Schistidium rivulare* (Brid.) Podp.
Thui reco	= *Thuidium recognitum* (Hedw.) Lindb.
Tort cffr	= *Tortella* cf. *fragilis*
Tort frag	= *Tortella fragilis* (Hook. ex Drumm.) Limpr.
Tort spp	= *Tortella* sp.
Tort incl	= *Tortella inclinata* Limpr.
<u>Tort tort</u>	= *Tortella tortuosa* (Hedw.) Limpr.

4 Field Experiments

Introduction

Bryophytes are an important component of alvar vegetation, not only in terms of biodiversity, but also in terms of the role they play at the ecosystem level. Previous studies have shown that bryophytes do not readily establish on their own on quarry floors (Schaefer and Larson 1997). Hence the need, if our goal is to establish alvar plant communities in depleted quarries, to develop restoration techniques that allow the successful establishment of bryophytes on bare limestone pavement.

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 practicioners.

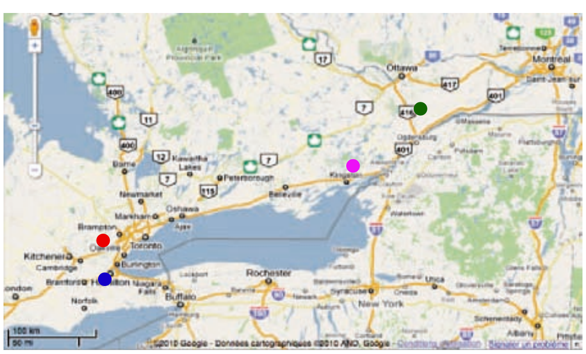

Figure 4-1. Location of our experimental sites. ● *Lawless Quarry;* ● *Hendry Quarry;* ● *Fletcher Creek Quarry;* ● *Toth Quarry.*

Methods

Site descriptions

During the course of the project, a total of eight moss introduction experiments were conducted in four quarries located across southern Ontario (Figure 4-1).

Lawless Quarry

Our first experimental site was located on Road 44 in Cristal Rock, near the junction of Highway 416 and Highway 401, Leeds and Grenville County, Ontario (N 44° 47' 11.9"; W 075° 29' 54.6"). In this report, we will refer to this site as "Lawless Quarry".

The floor of this quarry has two levels (Figure 4-2). The lower level covers about a fifth of the quarry and is filled with water, forming a shallow pool bordered by wetland vegetation. The second, higher level is flat, dry and mainly bare limestone, with some areas at the base of the walls partly colonized by mosses, trees and grasses. The quarry walls are high, with small trees and other vegetation on some of the wider ledges. The quarry has been out of use for several decades and its limestone floor subjected to weathering for many years. Substrate of the area where we conducted our experiments was composed of patches of bare limestone interspersed with areas where a thin layer of mineral soil (fines, sand and gravel) covered the rock surface (Figure 4-3).

Hendry Quarry

Our second experimental site was "Hendry Quarry". This quarry is located along Perth Road (Road 10) in Kingston, Ontario, between Bur Brook Road and Unity Road (N 44° 18' 29.9"; W 076° 30' 06.3").

Figure 4-2. View of Lawless Quarry, taken from the top of one of the cliffs. At the right, the pool on the lower level quarry floor.

The quarry walls are high on two sides, but nearly non-existent on the other sides. The quarry floor is gently sloped toward the high quarry walls and ends in a low area at the base of the south wall where some standing water remains for most of the growing season (Figure 4-4).

We conducted our experiments in the higher portion of the quarry floor, believing it to be outside the potential flood zone. The limestone pavement of the experimental area was generally covered with a thin layer of mineral soil (fines, sand and gravel), interspersed with smaller areas of bare weathered limestone. Some of the loose covering material may have been of exogenous origin, as the quarry might have been used for storage during road construction.

Figure 4-3. Substrate at Lawless Quarry, with areas of bare limestone interspersed with areas covered by a thin mineral soil layer.

Fletcher Creek Quarry

This quarry is located within the Fletcher Creek Ecological Preserve (Hamilton Conservation Authority), in the quadrant formed by Gore Road, Concession Road 7, Concession Road 1 and Road 6 South, in Puslinch Township, County of Wellington, Ontario (N 43° 25' 06.7"; W 080° 06' 09.3").

Experiments at Fletcher Creek were conducted in two areas of the quarry that were very different from each other in terms of substrate.

The first area (the "Old Site") is an area of bare limestone pavement that has been subjected to weathering for several decades (Figure 4-5). The second area (the "Young Site") is a sloped area that had been reworked by machinery and is bare of vegetation. The unweathered limestone surface is covered in places by shallow mineral soil, sand and gravel (Figure 4-6).

Figure 4-4. View of bare rock and thin mineral substrate at Hendry Quarry. At left, the pool in the lower area at the base of the cliffs.

Toth Quarry

The last experimental site, "Toth Quarry" after the name of its landowner, is located near Clanbrassil, Haldimand County, Ontario, along Haldimand Road 9, south of the junction of Haldimand Road 9 and 3rd Line Road (N 42° 58' 25.6"; W 079° 56' 41.2").

The high cliff bordering this quarry on one side was reworked mechanically by MAAP in 2007 to improve security at the site. Large areas of the quarry

Figure 4-5. Bare weathered limestone pavement at the Fletcher Creek Quarry "Old Site."

floor near the former cliff wall are covered by broken limestone rocks of various sizes. Other smaller areas are on flat, bare limestone (Figure 4-7).

Timeline

Three experiments were conducted at Lawless Quarry. Two of these experiments were set up in 2008 and the last one in 2009. All were monitored through 2011.

Two experiments were conducted at Hendry Quarry. Experiments at this site were set up in 2008 and monitored through 2011.

Two experiments were conducted at Fletcher Creek Quarry, one at each site (Old and Young). Both experiments were initiated in late summer 2010 and monitored through the fall of 2012. One experiment was conducted at Toth Quarry and followed the same timeline as the Fletcher Creek Quarry experiments.

Figure 4-6. Patches of bare limestone and thin mineral soil at the Fletcher Creek Quarry "Young Site."

Figure 4-7. View of the reworked cliff and surface at Toth Quarry.

Species used

Analyses of alvar and quarrry 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, species of mosses that inhabit early successional 'rocky' habitat were considered most appropriate and thus selected for the study.

Four species of mosses were used: *Tortella tortuosa*, *Syntrichia ruralis* (syn. *Tortula ruralis*), *Schistidium rivulare* (syn. *Grimmia alpicola*) and *Encalypta procera*. The first three—*T. tortuosa* (Figure 4-8), *S. ruralis* (Figure 4-9) and *S. rivulare* (Figure 4-10)—can be found in alvars as well as in depleted quarries.

The fourth species used was *Encalypta procera* (Figure 4-11). The species is found in alvars but it was not recorded in Guelph previous quarry vegetation surveys. Our team found *E. procera* at Fletcher Creek Quarry on an old, well-vegetated limestone ledge bordering a pool, near clumps of five- to six foot-tall white cedars (*Thuja occidentalis*). Therefore, although we know from this occurrence that *E. procera* can be present in vegetated areas of

Figure 4-8. Tortella tortuosa.

Figure 4-10. Schistidium rivulare.

very old quarries, this species does not seemingly colonize quarry floors readily, making it an interesting candidate for the current study.

Factors studied

Three main environmental factors were examined in our experiments:

1. the type of substrate,
2. the use of a protective mulch cover and
3. changes in microtopography made in order 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 more than one year. This allowed the analysis of interactions between species, environmental factors and time.

Table 2 summarizes the factors that were addressed in each of the eight experiments. Details are provided in the text below.

Effect of moss introduction and comparison between moss species

Two experiments conducted in 2008 at Lawless Quarry and at Hendry Quarry (Table 2), included a control where moss propagules were not introduced. Propagules, or diaspores, are any portion of a plant (e.g. a seed, a cutting, a demma, a spore, a

Figure 4-9 Syntrichia ruralis

Figure 4-11. Encalypta procera.

Table 2. 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) 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) Effect of a straw mulch cover	2009, 2010
Lawless Quarry	October 2008	*T. tortuosa, S. ruralis*	Effect of substrate type (rock vs thin soil) 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) 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) 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) Effect of a straw mulch cover	2011, 2012

[1]*Detailed accounts of the methods, results and conclusions for each experiment are presented in Appendixes A1 to A8*

fragment, 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—namely airborne spores—could be favored by changing environmental conditions alone.

In all experiments but one (Table 2), the responses of two or more species of mosses to one or more environmental factors were compared. *T. tortuosa* was used in all eight experiments. *S. ruralis* was used at all four sites, but not in all experiments. *S. rivulare* was used at all sites except Hendry Quarry. *E. procer*a was used only at Fletcher Creek and Toth Quarries.

Effect of mulch cover

Seven experiments examined whether the addition of a straw mulch cover to protect introduced propagules improves moss establishment success in comparison to treatments where no straw mulch is added. 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, two conducted at Lawless Quarry, one conducted at Hendry Quarry and one conducted at the Fletcher Creek Quarry, examined how moss establishment success on bare limestone compares to establishment in areas where a thin layer of mineral soil covers the bare rock.

A fifth experiment, initiated at Lawless Quarry in fall 2009, 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

The 2010 Toth Quarry experiment examined how moss establishment success on bare limestone compares to establishment in areas where the limestone substrate was altered by heavy equipment and covered by broken rocks of mixed size.

Two experiments conducted in 2008 at Lawless and Hendry Quarries examined the effect of a sheltering topographical element on moss establishment success. The topography tested consisted of low contour ridges made of small rocks and surrounding the introduced propagules. This sheltering effect was compared to the effect of straw mulch.

Effect of time since introduction

Two experiments conducted at Lawless Quarry and one conducted at Hendry Quarry were monitored over a three-year period, with measurements taken at least once a year. All other experiments were monitored over a two-year period.

Experimental designs

All experiments that were part of this study were conducted using standard factorial experimental designs. The designs varied between experiments. Depending on factors to be tested and site constraints, a randomized complete block design, split-plot randomized design, split-plot randomized complete block design or split split-plot randomized design was used.

Figure 4-12. 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.

The choice of design was based on the feasibility and convenience of applying a treatment to a single unit or to a group of units. Experimental design affects how treatments are randomized to experimental units as well as the type of model that is used for statistical analyses.

Although the designs varied, all experiments had a common "feel," as our basic experimental units were the same for all experiments, i.e., a 1 m x 1 m square at the centre of which a 50 cm x 50 cm area was used for moss introduction (Figure 4-12).

In some experiments, the 1 m x 1 m units were considered as plots and grouped into blocks of two units that were replicated a number of times. This design is known as a randomized complete block design. In experiments where it was more convenient to apply a treatment to a group of units than to a single one, for example in cases where we wanted to test the effect of substrate type, a split-plot design was used. Units were grouped in plots of two or three, some located on one type of substrate and some on the other. Units were then considered as subplots, for example subplots with and without straw mulch, or with and without sheltering topography or mulch (Figure 4-13). This type of design is a split-plot or a split split-plot design.

Most often, the 50 cm x 50 cm central area where moss introduction took place was split into two or four quadrants in which the different species of mosses were introduced (Figure 4-13). These smaller units then became subplots or sub-subplots, and the experiments were analyzed accordingly.

Experimental Methods

Although the eight experiments differed from each other by the factors studied, all were conducted using comparable moss introduction techniques and treatment application methods.

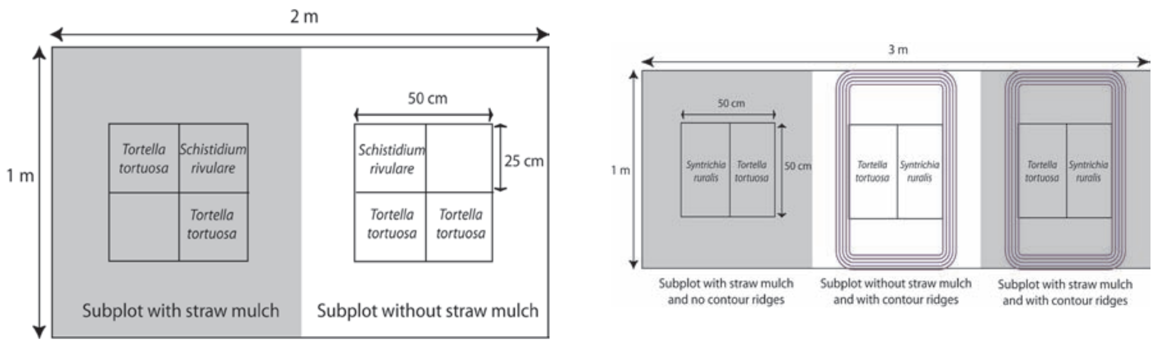

Figure 4-13. Examples of plot layouts used in split split-plot randomized design experiments. The 2 m x 1 m (left) and 3 m x 1 m (right) experimental plots are composed of 1 m x 1 m subplots. In each subplot, the central 50 cm x 50 cm area is divided into sub-subplots that receive different species. In the example on the right, contour ridges were built around the moss introduction area of the subplots on the right drawing

Moss introduction

Moss colonies from the targeted species were picked by hand a day or two prior to moss introduction (Figure 4-14) and kept in breathable Ziploc™ vegetable plastic bags in the dark or in the shade. 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 moss colonies were broken apart by hand into a mixture composed of individual stems, clumps of a few stems and fragments of mosses. This material was then divided 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 units. Propagules were spread by hand, with care taken to ensure even distribution over the entire surface to be covered, including edges.

As mentioned previously, the basic experimental units were 1 m x 1 m. Moss introductions were only done in the central 50 cm x 50 cm portion of these squares (Figures 4-12 and 4-15). This allowed a 50 cm buffer between introduction areas located in adjacent units.

Mulch treatments and mulch application

Straw mulch used in the experiments was purchased locally and was either oat, rye, spelt or wheat straw,

Figure 4-14. Hand-collecting colonies of <u>Tortella</u> <u>tortuosa</u>. The green box is 25 cm x 25 cm and allowed us to measure the surface collected.

Figure 4-15. View of an experimental plot, with two subplots, one covered with mulch and the other not.

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 4-15). 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 it was applied (i.e. wider than the the 50 cm x 50 cm moss introduction area).

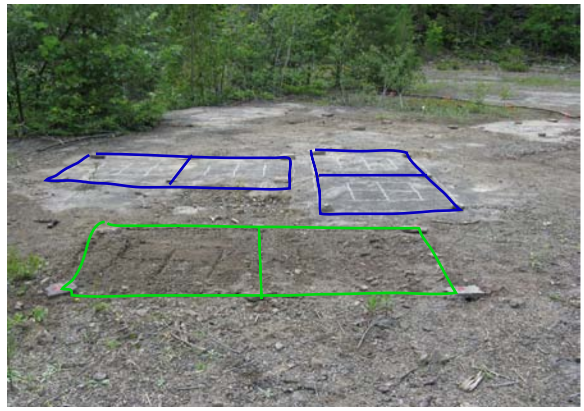

Figure 4-16. Initial steps to establish an experiment on the effect of substrate on moss establishment. Some plots are on thin soil (green), others on bare rock (blue).

Substrate and substrate amendments

In the four experiments that examined the effect of a thin soil substrate (Table 2), two or three 1 m x 1 m units were grouped in a plot and positioned on bare limestone or in areas where the limestone pavement was covered with a thin layer of sand, gravel and fines (Figure 4-16). Moss establishment on these plots was then compared over several seasons.

In a fifth experiment we examined how actively adding a thin layer of soil amendments—both mineral and organic—on bare rock would affect moss establishment (Table 2, Lawless 2009 experiment). The amendments tested were horticultural sand or 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 (¾" clean limestone) were built around each plot in order to prevent amendments from moving between adjacent plots (Figure 4-17A). The sand or sand and peat mixture was sprinkled on plots in an eight millimeter layer, (8 L 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 4-17B). All plots were covered with straw mulch.

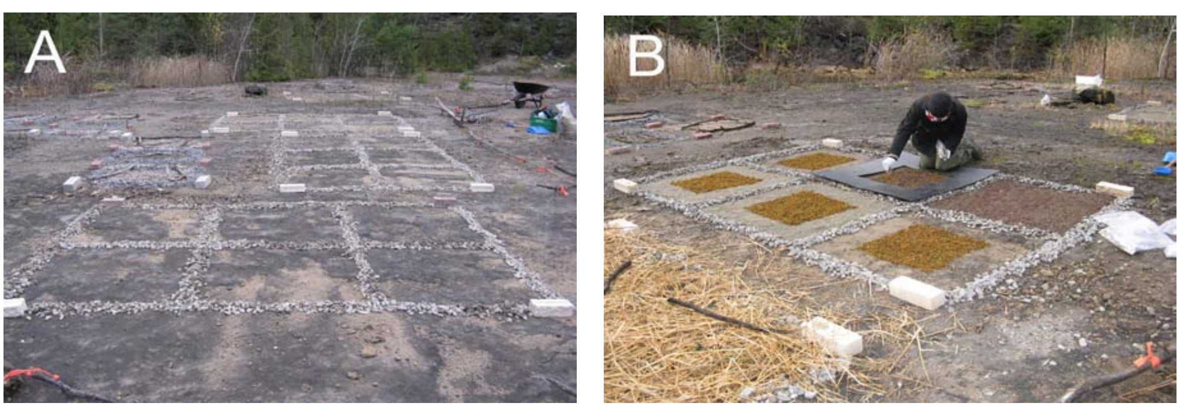

Figure 4-17. Images of the Lawless 2009 experiment on substrate amendments. A) Contour ridges delineating experimental plots within a block. B) Introducing propagules on the central 50 cm x 50 cm area of a plot. Notice the grey (sand) and brownish (sand + peat) substrate amendments.

Figure 4-18. Images of the 2010 Toth Quarry experiment on the effect of substrate type on moss establishment. Left: bare, flat limestone substrate. Right: limestone substrate covered with rocks of various sizes.

Microtopography

The sheltering topographical element we tested at Lawless and Hendry Quarry (Table 2) consisted of a 1 m x 50 cm rectangle that was delineated by a 5 cm to 10 cm high contour ridge made of small rocks (¾" clean limestone) (Figure 4-19).

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

In an experiment conducted at Toth Quarry in 2010 (Table 1) 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 4-18). 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 4-20, 4-21 and 4-22). 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

Figure 4-19. 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.

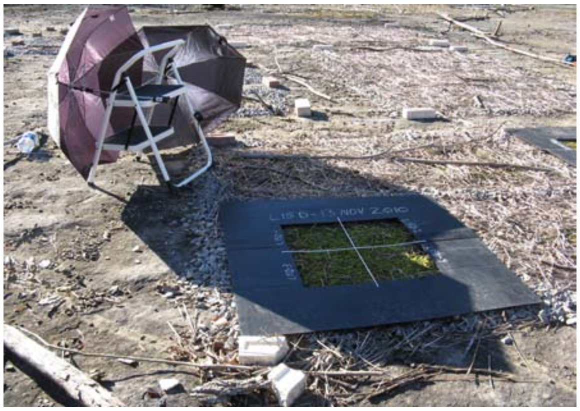

Figure 4-20. Cut-out plastic sampling frame. Umbrellas were used to evenly shade the plots when taking pictures, for better results.

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.

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 evolution of moss cover. The repeated factor was the time of measurement. The MIXED procedure of the SAS program was used with a REPEATED statement and a covariance structure that minimized the Akaike criterion. Kenward-Roger's method was used to calculate the degrees of freedom. Pairwise comparisons were made using protected Fisher's LSD (least significant difference).

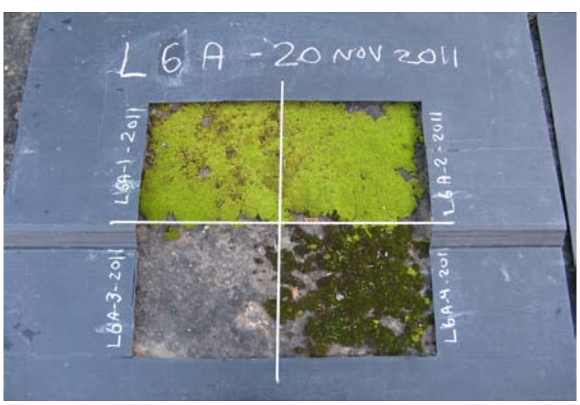

Figure 4-21. Moss establishment of T. tortuosa (pale green) and S. rivulare (dark green) after three years on a mulch plot, and comparison to an area (bottom left) where no moss propagules were introduced.

Figure 4-22. Estimating moss cover on experimental plots.

The analyses were run on untransformed data when they met the assumption of normality of residuals. In some cases, square-root transformed data were used as their residuals met the assumption of normality whereas residuals of untransformed data did not. In some cases, neither the untransformed or transformed data met the assumption of normality of residuals. In these case, the asymmetry and flatness coefficient of one data set were better than those of the other and fairly close to those of a normal distribution. The analyses were therefore performed on that data set. As the analysis of variance is fairly robust to non-normality, we considered the results to be valid.

Results

Effect of moss introduction and comparison between species

The first experiments conducted at Lawless Quarry and Hendry Quarries included a control without moss introduction to determine whether establishment from naturally occurring propagules could be favoured by changing environmental conditions alone.

Results of these trials were very conclusive. No moss establishment occured in controls, except at the edge of a quadrant where mosses from colonies from adjacent quadrants expanded into an empty one (Figure 4-21 and 4-23). As a result of this finding and as the number of experimental plots was often constrained by space, conrol treatments without mosses were not repeated in later experiments.

With appropriate mulching and substrate conditions (see examples in Figure 4-23 and 4-24), moss establishment was succesful for all species tested and in all sites and experiments.

T. tortuosa was generally more successful than the other species tested, at least in the short term.

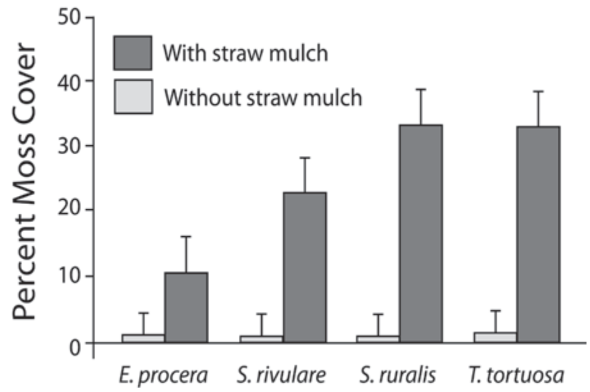

Figure 4-24 Effect of mulching on the establishment of four species of moss after one growing season at the Flecher Creek Quarry "Young Site" (Mean ± SE, with substrates pooled).

At Lawless Quarry, *T. tortuosa* reached a nearly full cover within two years on mulched plots. In experiments monitored over longer periods, percent cover of slower-establishing species such as *S. rivulare* continued to increase over the years and some reached levels comparable to that of *T. tortuosa* (Figure 4-23).

Interestingly, *E. procera*, a species that is not often found in depleted quarries, was able to establish when introduced on the bare limestone and thin mineral soil of depleted quarries (Figure 4-24).

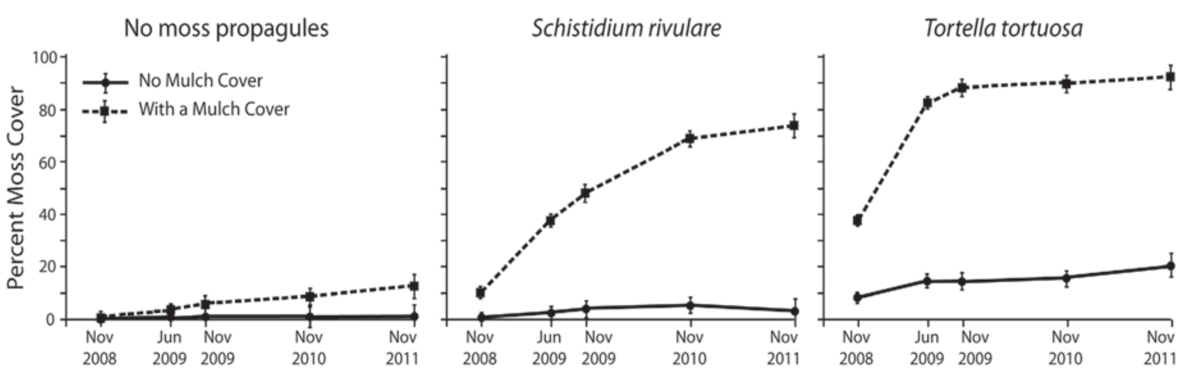

Figure 4-23. Results from the June 2008 experiment at Lawless Quarry: Effect of mulching and propagule introduction on moss establishment over a three-year period (Mean ± SE, two substrates pooled).

Figure 4-25. 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. Right: bare rock substrate; Left: bare rock covered with a thin layer of soil.

Effect of mulch cover

In all experiments where we compared mulched and non-mulched plots, moss establishment was far more succesful when a mulch cover was provided. As shown in Figure 4-23, 4-24 and 4-25, moss establishment was very poor or absent on non-mulched plots and, when some initial establishment took place, moss cover failed to increase or even decreased over time.

In one particular case mulch failed to improve moss establishment: at Toth Quarry, when propagules were introduced on a substrate composed of broken limestone rock of various size (Figure 4-29). This experiment is discussed in more detail in the next section (Effect of substrate type and substrate amendments).

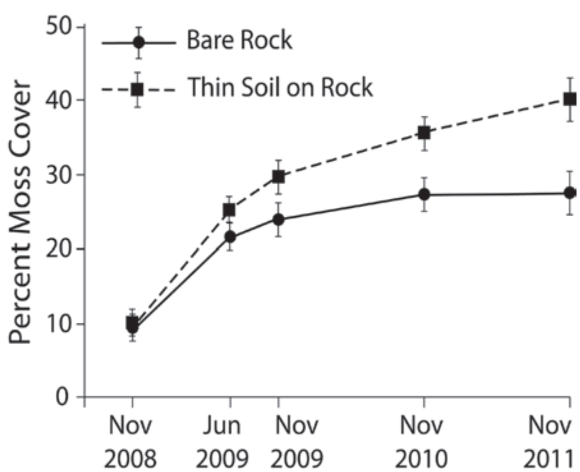

Figure 4-26 Effect of substrate type on the establishment of mosses on a quarry floor (Mean ± SE, Moss and mulch factors pooled). Lawless Quarry, June 2008 experiment.

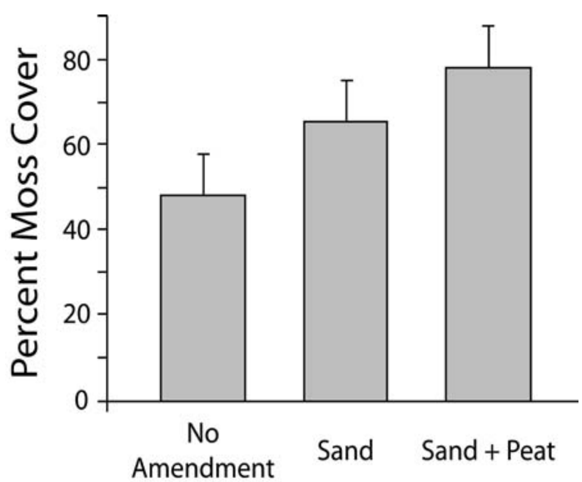

Figure 4-27. Effect of the addition of a thin layer of amendments over a bare limestone substrate prior to moss introduction (Mean ± SE, 2010 and 2011 data pooled). Lawless Quarry, October 2009 experiment.

Effect of substrate type and substrate amendments

In most experiments where we compared moss establishment between plots located on bare rock and plots where a thin layer of mineral soil covered the bare limestone, moss establishment was significantly better on thin soil (Figures 4-26).

At Fletcher Creek Quarry, results after one year did not show significant differences between plots on mineral soil and on bare rock, but visual observations suggested that minor differences were present and could develop into significant differences over time (Campeau, personal observations). Unfortunately, these plots were destroyed in the second year by trespassers on ATVs and no further data could be recorded for this trial.

Adding a thin layer of sand or sand and peat amendment on bare rock prior to moss introduction had a similar effect as the presence of naturally occurring mineral soil: moss establishment was significantly improved on amended plots (Figure 4-27). No significant difference could be detected between sand-treated and sand and peat-treated plots, although moss cover was slightly better on the later.

Figure 4-28. T. tortuosa establishing between rocks on a non-mulched plot. Toth Quarry, 2010 experiment, image taken in 2011.

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 4-30 and 4-31).

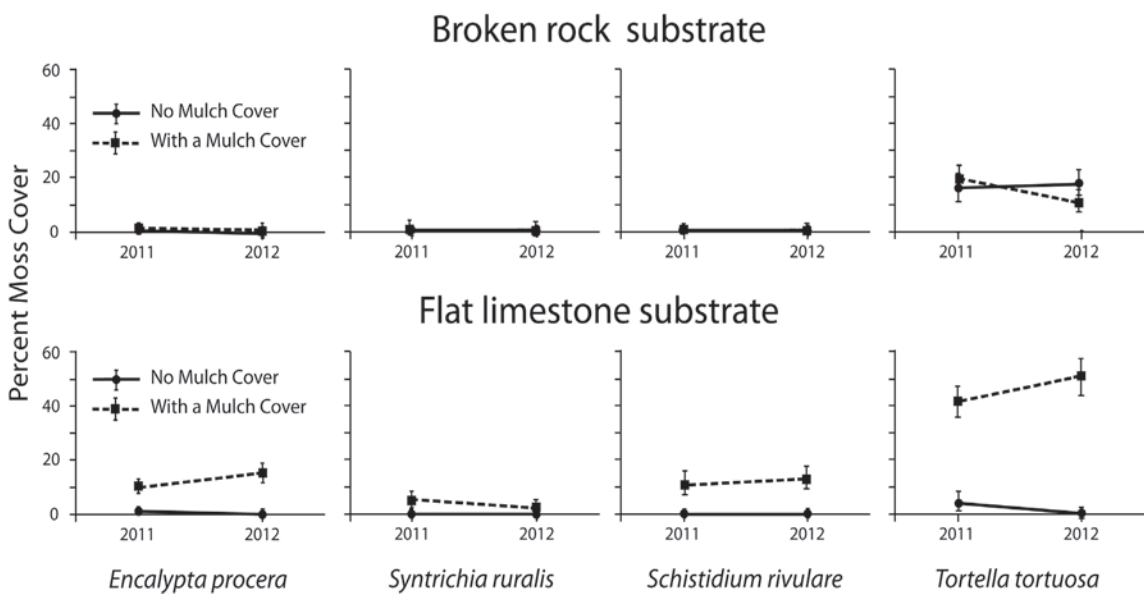

Figure 4-29. Effect of mulch cover and species on moss establishment on a flat limestone substrate and on a substrate composed of broken rocks of various size (Backtransformed mean ± SE). Toth Quarry, August 2010 experiment.

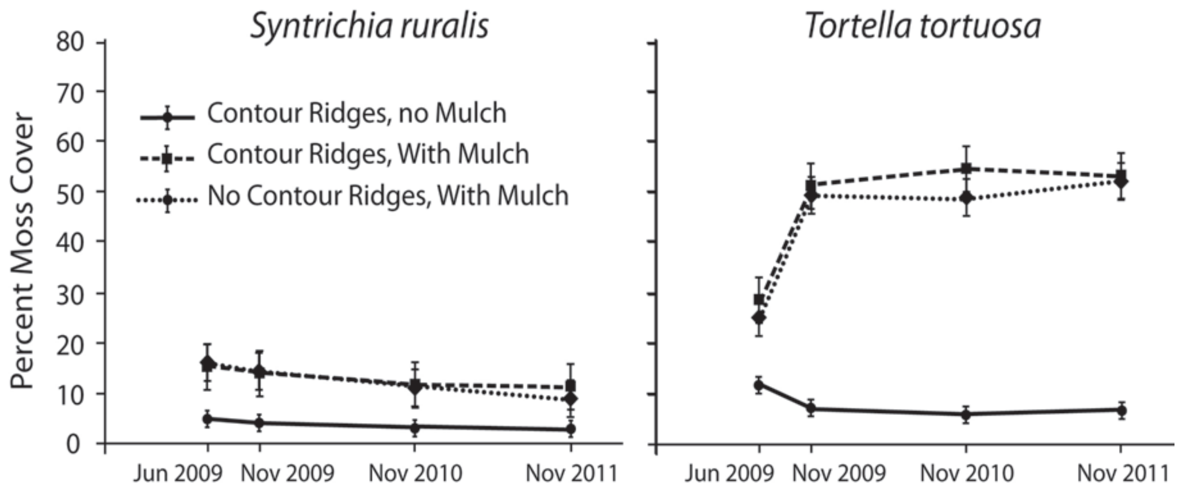

Figure 4-30. Effect of sheltering topography on the establishment of two species of moss introduced on a quarry floor, and comparison to the effect of straw mulch (Mean ± SE). Lawless Quarry, August 2008 experiment.

In plots with rock ridges but without mulch, moss propagules were displaced over time tended to aggregate along the rock ridges, out of the area where we took percentage cover measurements (Figure 4-31). Yet moss establishment in this treatment, even when considering these displaced propagules, was low in comparison to that in plots with straw mulch (S. Campeau, personal observations).

Results obtained at Toth Quarry showed that moss establishment was on a substrate composed of rocks of various size was generally not better than on flat limestone (Figure 31). Although some mosses, especially *T. tortuosa*, developed between rocks early in the experiment (Figure 4-28), moss coverage failed to increase between year one and year two and overall success was lower than on flat pavement for three out of the four species tested (Figure 4-29).

Furthermore, on this irregular substrate, mulch failed to provide its usual benefits for mosses (Figure 4-29). Our 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, smothering the developing propagules.

Figure 4-31. View of a sheltering rock ridge on moss establishment. Lawless Quarry, August 2008 experiment, images taken in 2011. 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 is left after three years. One half of each subplot received T. tortuosa (pale green). The second half received S. ruralis (darker green).

Effect of time since introduction

On mulched plots, moss cover increased with time at a rate that differed between species. Once full cover was nearly attained, moss growth continued, as both the density and the height of moss colonies increased in subsequent years (Figure 4-32). Unless disturbed, mosses established from introduced propagules developed into well-formed, stable and natural-looking colonies of their respective species..

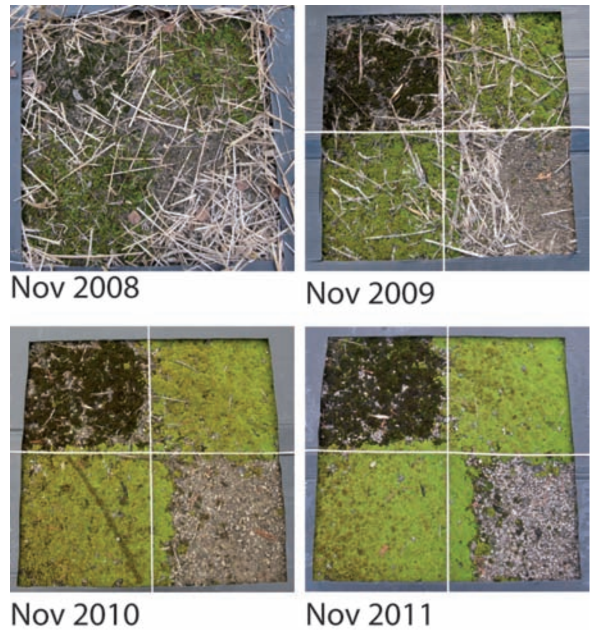

Figure 4-32. Change in moss cover in a mulched plot over the course of the Lawless Quarry June 2008 experiment. This plot is on thin soil. Most of the remaining straw mulch was removed prior to taking pictures. Hardly any straw was left by the end of the third year. The pale green moss is T. tortuosa; S. rivulare is a darker green.

Flooding and other disturbances

At Hendry Quarry, spring and summer flooding that followed snowmelt of important rain events destroyed a large number of experimental plots (Figure 4-33). At Toth Quarry, one experimental plot was destroyed by temporary flooding. This plot was located in a lower area at the base of a cliff (Figure 4-34). Even at Lawless Quarry, where a pool at a lower level of the quarry likely gathers a good portion of excess water, rivulets formed during heavy rains washed away some plots located from our experiment on substrate amendments (Figure 4-35).

At Fletcher Creek Quarry, it is not flooding but trespassers on ATVs that caused us to lose a number of experimental plots in their second year.

Figure 4-33. Location of the plots that were lost to flooding in 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 4-34. Inundated plot at Toth Quarry.

Figure 4-35. View of the Lawless Quarry,October 2009 experiment in Fall 2012. Plots to the right were washed away by heavy rains.

Discussion

Can we establish mosses in quarries?

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

Not only were the mosses successfully established at all our four sites but they also thrived. Unless disturbed by flooding or by humans, the newly established colonies continued to densify and expand laterally over the years (Figure 4-32). All species we tested were successful in one trial or another, although colony development was found to be slower in some species than in others.

Larson et al. (2006) demonstrated that for alvar vascular plant species that are absent from depleted quarries, seed limitation (i.e. seeds not reaching the empty habitat) is the principal factor limiting colonization. For mosses the picture may be different.

As for many vascular plants, introduction is needed in order to get moss species to establish rapidly and to a large extent. But contrary to what was found for vascular plants however, some manipulation of the environment such as the use of a protective mulch cover is needed to ensure the successful establishment of moss propagules on limestone pavement. Thus, the establishment of mosses in quarries is limited by both the dispersion capacity of the different species and by environmental conditions at the quarry floor level.

All species tested here are early successional, rocky habitat alvar species and are most suited for the initial stages of rehabilitating quarry floors. Alvar species that are found further along the soil depth, moisture and shade gradients are even more likely to require 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 success in depleted quarries: the use of straw mulch to cover and protect moss propagules after their introduction on bare limestone pavement (Figure 4-36).

This result was found to be repeatable over the seasons, years and sites. All trials demonstrated the positive effect of straw mulch on moss establishment and growth. The only exception was when mosses were introduced on an irregular substrate composed of crushed rocks of various sizes.

In comparison, when moss propagules were introduced without straw mulch cover, very little establishment could be detected after a year, and moss cover stagnated or even decreased afterward. 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, moss colonies continued to grow and remained healthy (Figure 4-36 and 4-38).

Covering propagules with straw mulch has also been shown to be of utmost importance for *Sphagnum* moss establishment 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.

At first glance, there seems to be little comparison between the waterlogged, acidic, organic substrates of harvested peatlands and the drought-prone, calcareous rock substrates of quarry floors. Yet, both ecosystems have in common that they represent extremes in terms of plant growing conditions. It is therefore very interesting to see that a technique as simple as mulching can be used successfully in both environments to establish a moss cover.

The role of substrate and amendments

The presence of an existing thin soil layer composed of sand, gravel and fines on the quarry floor enhance moss establishment. This thin layer, composed mainly of minerals and organic matter may help in at least two ways:

4. by helping keep moss fragments in place during early establishment despite wind and rain;
5. by storing water that keeps fragments moist longer after a rain even.

Even if significant, the positive effect of a thin layer of soil on moss establishment is not as important as the stricking, positive effect of straw mulch on moss propagule establishment.

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 millimetres of sand or sand and peat.

Larson et al. (2006) indicated that in order to favour the establishment of alvar vascular plants seeded in quarries, the existing soil should not be removed. Although not essential, the addition of sand and

Figure 4-36. 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. Some of these colonies are on rock (front, to the right), others are on thin mineral soil (front, to the left).

Figure 4-37. The weathered floor of two old quarries with mosses growing in the cracks and among pebbles on the limestone pavement.

organic matter will add nutrients, fines and carbon may provide some benefits to the plants. Their recommendation was that the amended soil depth should not exceed 2 cm.

For both vascular plants and mosses, substrate amendments are therefore not essential to ensure establishment in older quarry sites where a thin layer of soil is already present. In younger quarries or in sites with large areas of bare limestone, adding a thin layer of sand and organics prior to seeding and propagule introduction may prove beneficial.

Microtopography

Sheltering propagules using low rock ridges provided no benefits and could not replace the use of mulch.

Moss establishment was not enhanced on a substrate composed of rocks of various size, and especially not on mulched plots. This result was unexpected and is somewhat counter-intuitive as, in old quarries, mosses are often found in cracks or in areas with small rocks and pebbles (Figure 4-37).

In peatland restoration, increasing the microtopography of a site by harrowing, ploughing or rendering into shallow track-and-ridge microtopography made by the tracks of a bulldozer does not improve sphagnum moss establishment when compared to a flat site (Price et al. 1998). These authors showed that, as expected, negative elements of the microtopography were wetter and cooler than positive relief elements. Under a mulch, however, the negative elements provided no additional benefits in terms of temperature or soil moisture conditions. Taking into account the poorer performance of positive relief elements, even when covered with mulch, the creation of surface microtopography reduced the moisture of the site overall. Similar phenomena may explain the poor establishment success of mosses on a broken rock aubstrate at Toth Quarry.

Stabler (2009) showed that increasing the spatial heterogeneity of the rock pavement using a rock hammer 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 in the microtopography of quarry floors. More trials are however needed to assess the effect of microtopography more thoroughly, as only one experiment on this topic was conducted during the course of the study. Using other patterns of substrate heterogeneity, with topographical elements of a different size may lead to different results.

Flooding disturbances

Flooding was not among the factors we originally planned to study during this project. However, our observations showed that this factor may be very important to consider in quarry restoration. Even very shallow flooding (sheet flooding) or infrequent flooding events following hard rains were sufficient to displace propagules and hinder moss establishment. Potential for water movements and pooling of excess water therefore need to be taken into account in quarry restoration.

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 sometimes 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 of other plants as well.

Figure 4-38. View of Lawless Quarry floor in 2011, with newly established colonies of the moss T. tortuosa readily visible against the grey limestone in plots from our 2009 experiment.

5 Conclusions and Recommendations

Figure 5-1. 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 5-2. 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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Figure 6-2. Tree estabablishment on an old abandoned quarry.

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Figure 7-1. Northern Green Frog in a pond at Fletcher Creek Quarry.

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