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# Towards calcareous wetland creation in flooded abandoned aggregate quarries: A 3-year field mesocosm study

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ABSTRACT

The purpose of this study was to demonstrate the feasibility of the rehabilitation of abandoned aggregate quarries to calcareous wetlands through a growth experiment at the quarry floor. We tested the effects of planting substrate (fine screenings, coarse rock, transplanted peatball, and topsoil addition to screenings) and springtime water depth (+15, 0, and −15 cm relative to ground surface) on the growth of *Carex aquatilis* over 3 years. Survival rate of the transplanted material was 100%. Minimal growth was observed after the first growing season, but by the end of the third growing season the transplanted material had added on average 80, 4, and 3 shoots in the topsoil-amended, intact peatball, and coarse rock treatments, respectively, but lost on average 4 shoots in the fine screenings treatment. The addition of topsoil significantly increased final aboveground biomass (285 ± 49 g per plot) compared to the peatball (40 ± 16 g), rock (36 ± 11 g) and screenings (35 ± 21 g) treatments, which were not significantly different. The effect of water depth did not lead to overall significant differences, as *Carex aquatilis* ramets were capable of growing in springtime water levels from 15 cm above to 15 cm below ground surface. Our data demonstrate that some flooded abandoned aggregate quarry floors represent suitable sites for conversion to calcareous wetlands, even with a strategy of minimum maintenance, and that wetland species are capable of growth in these largely inorganic settings.

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## 1. Introduction

Calcareous fens are wetlands that are fed principally by groundwater rich in calcium and magnesium carbonate (Komor, 1994; Almendinger and Leete, 1998), exhibit very high species diversity (Motzkin, 1994; Johnson and Steingraeber, 2003), and serve as regional refugia for a number of rare plant taxa (Nekola, 2004; Bowles et al., 2005). Historically, calcareous fens have been subject to significant loss and degradation throughout North America and Europe due to groundwater extraction and/or diversion (Gilvear et al., 1993; Wassen and Joosten, 1996), as well as nutrient enrichment from encroaching agricultural land use and atmospheric deposition (Drexler and Bedford, 2002; Pauli et al., 2002; Lucassen et al., 2006). Because of their high biodiversity value these wetlands are now frequently targeted for protection and conservation (Bedford and Godwin, 2003). The restoration of degraded peatlands (e.g., Price et al., 1998; Sottocornola et al., 2007; Lucchese et al., 2010) and of degraded calcareous fens in particular (e.g., Beltman et al., 1996; Vinther and Hald, 2000; Jansen et al., 2001; Lamers et al., 2002) is the focus of much research. Recently, Amon et al. (2005) have demonstrated the possibility of calcareous fen creation on sites without evidence of former fen presence. We follow upon the concept presented by Amon et al. (2005) by initiating a research program to investigate the potential to create calcareous wetlands in a novel landscape setting: an abandoned flooded dolomite quarry floor.

In southern Ontario, Canada, the abundance of calcareous bedrock and glacial drift has generated an extensive quarrying industry for limestone and dolostone aggregate extraction. The Ontario Ministry of Natural Resources has mandated some form of site restoration and remediation must take place following the cessation of aggregate extraction (OMNR, 2006). Conversion to an open water ecosystem is currently the favoured rehabilitation method of the Ontario aggregate industry for below-water table extraction quarries; however, this produces an ecosystem of limited ecological and environmental value (Corry et al., 2008). Due to the presence of extensive calcareous groundwater discharge in these settings one very attractive option for restoration is the conversion of these abandoned quarries to calcareous wetlands. As a preliminary step in investigation of the

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feasibility of quarry conversion to calcareous fen we tested the effects of planting substrate and water depths on the growth of a single species: *Carex aquatilis* Wahlenb. (water sedge). This species is a fen generalist, that is, not a true calciphile, but a robust, perennial sedge (Bernard, 1990) that is frequently found in calcareous fens (Gignac et al., 2004), and is a dominant vascular plant in calcareous fens surrounding the abandoned quarry.

Through the use of controlled growth experiments previous research has revealed much information on the predominant variables affecting vascular wetland plant growth and biomass. Several studies have demonstrated that the relative availability of nutrients, particularly the N to P ratio, exerts a significant control on the biomass of wetland sedges and grasses grown under experimental conditions (Güsewell and Bollens, 2003; Güsewell, 2005c). Water regime has also been the subject of much recent research, and Kotowski et al. (2001) found that water depth had little effect on the growth of some wetland species grown at water levels from 0 to 45 cm below ground surface. Güsewell et al. (2003) found that the effects of water regime on growth were minor compared to nutrient levels, while Wetzel and van der Valk (2005) reported that hydroperiod had little influence on the growth of *Carex stricta* Lam., a species closely related to *C. aquatilis*. However, Fraser and Karnezis (2005) found significant differences in biomass in several wetland sedges grown in water levels that differed by just 2 cm. Consequently, a consensus on the effects of water availability on wetland sedge species growth is currently lacking.

In contrast to the research on nutrients and water levels, the influence of the physical structure of the planting substrate has received little attention. Indeed, in an effort to isolate the effects of nutrient additions and/or water regime, the planting material is not only standardized, but often consists of sand or sand-peat mixture (Wetzel and van der Valk, 1998, 2005; Güsewell and Freeman, 2005), mineral soil (Budelsky and Galatowitsch, 2000, 2004; Miller and Zedler, 2003; Perry et al., 2004), or horticultural mould (Güsewell, 2005a,b; Güsewell and Bollens, 2003). These planting conditions may be advantageous for determining other controlling factors on plant growth, but they do not represent the *in situ* growing conditions, and therefore mask natural variability. Furthermore, as applied to restoration efforts, it is particularly useful to assess plant success in conditions as close to the natural setting as possible.

While great effort has been devoted to carefully designing controlled experiments to investigate environmental constraints on the growth of wetland vascular vegetation, researchers have conducted these experiments over a very variable timeframe, sometimes too short to be of much use for restoration purposes. Indeed, there are many examples where growth experiments are run for less than a full growing season (<4 months: Wetzel and van der Valk, 1998, 2005; Kotowski et al., 2001; Güsewell and Bollens, 2003; Janecek et al., 2004; Güsewell, 2005a,b). There are also a number of studies lasting for approximately one full growing season (4–8 months: Visser et al., 2000; Miller and Zedler, 2003; Perry et al., 2004; Fraser and Karnezis, 2005; Güsewell and Freeman, 2005; Kettenring and Galatowitsch, 2007). Controlled growth experiments in which treatment responses are monitored for two or more growing seasons (e.g., Yelka and Galatowitsch, 1999; Budelsky and Galatowitsch, 2000, 2004; Güsewell, 2005c; Güsewell et al., 2003; Edelkraut and Güsewell, 2006; De Steven and Sharitz, 2007) are more useful for the study of vegetation ecology in natural and restored sites. In this first step towards full quarry rehabilitation to calcareous wetlands we chose to study the growth of *Carex aquatilis* in this setting over three growing seasons.

Our restoration design of the abandoned aggregate quarry adopted the concepts of minimum maintenance and self-design (Mitsch and Gosslink, 2007). That is, in contrast to the piping and valve efforts of Amon et al. (2005) to regulate water flow, because of the groundwater discharge zone created by the quarrying activities, we chose to assess wetland initiation with the *in situ* water availability. Moreover, our continuing restoration efforts are investigating the natural development of the rehabilitated quarry. The purpose of the present study was to determine whether sedges typically found in organic-rich substrate would successfully transplant and grow in a mineral substrate setting, and what physical environmental conditions yielded the greatest success. We used field mesocosms to investigate our research questions. As the overall goal was to rehabilitate an abandoned quarry to a calcareous wetland, we adopted this approach, even though it is less controlled than utilizing greenhouse experiments and/or smaller microcosms. The following questions were posited. (1) Will transplanted ramets of *C. aquatilis* initially survive and subsequently grow over a 3-year period in largely inorganic mineral substrate that may be found in quarry sites post-extraction? (2) Will transplanted ramets demonstrate a potential for sexual reproduction? (3) In the rehabilitated quarry setting, what are the effects of water depth and substrate type on *C. aquatilis* annual growth, reproductive potential, and aboveground biomass over the 3-year period? With this last question, we hypothesized the following in relation to our treatments (discussed below): the sedges in the peatball substrate would perform the best, in terms of survival, growth, reproduction, and aboveground biomass, with the rock treatment yielding the least growth; and, the intermediate water depth would prove most beneficial to the sedges, with the shallow water treatment proving worst.

## 2. Study area

The quarry rehabilitation and calcareous wetland creation experiment is located in the Fletcher Creek Ecological Preserve, a 197-ha natural area owned by the Hamilton Conservation Authority in Puslinch Township, 30 km north of Hamilton, ON, Canada. Many small, isolated calcareous fens are situated throughout the ecological preserve, and a large portion of this property is designated as a provincially significant Wetland as well as an environmentally sensitive area. The preserve is underlain mostly by dolomite of the Guelph formation, with an overburden of glacial outwash silt in the northwestern most section (Chapman and Putnam, 1984). The preserve is a regional groundwater discharge area from the Galt moraine to the northwest and serves as one of the headwaters to Spencer Creek, a key river that flows through Hamilton into Lake Ontario.

Historically, Steetley Industries operated a small (~3.5 ha) aggregate quarry in the northeast corner of the preserve. Operation of this quarry consisted of a below-water extraction of ~0.8 ha that was between 4 and 6 m in depth. The operation was abandoned abruptly in the early-1930s and no attempt was made to rehabilitate the site. In addition to the 4–6 m below-water table extraction, exposed dolomite cliff faces of up to 6 m were created. Due to potential liability regarding the high cliff faces, in 2003 the Hamilton Conservation Authority with the assistance of The Ontario Aggregate Resources Corporation decided to lower the quarry walls and rehabilitate the quarry into a calcareous wetland.

In 2003–2004 the quarry walls were lowered using a hoe ram and backhoe, and the associated shot rock was positioned to create a landscape design consisting of four shallow bays surrounding a slightly deeper central pool. Lowering the cliff faces into the quarry is a relatively common rehabilitation technique used in the aggregate industry (OMNR, 2006). The use of the native dolomite shot rock to create these shallow bays ensured that the groundwater quality and quantity remained unchanged. At the start of the present study, the study area was a 0.6 ha body of water with a maximum depth of one meter underlain by the dolomite shot rock and/or intact dolomite. The smallest of the created bays, underlain entirely by the parent Guelph Formation dolomite with a gentle slope, was chosen for the experimental set-up to test the feasibility of these settings for sites of calcareous fen creation.

## 3. Methods

### 3.1. Experimental set-up

Transplant material was obtained from the largest natural reference fen in the Fletcher's Creek Ecological Preserve. Plant material was extracted in May 2005 to a peat depth of 30 cm and subsectioned at the quarry into 10 cm diameter plugs for transplant. As *Carex aquatilis* (water sedge) was the dominant vascular species in the portion of the natural site under study at that time an effort was made to select sections of the fen for removal that contained >75% water sedge. Where possible, further discrimination was made in the preparation of the small transplant plugs; that is, easily removable non-water sedge vegetation was separated from the plugs. Water sedge ramet plugs were placed in 30 cm × 30 cm × 30 cm plastic garden bins with associated potting material.

Four substrate treatments were tested in the experiment, spanning a range of cost-alternatives to quarry rehabilitation (Fig. 1). The 'peatball' treatment consisted of inserting the intact plant-peat monolith into stabilizing crushed dolostone with median *b*-axis diameter of 25 mm, referred to as screenings. This represents the most expensive treatment option, as it requires procurement of natural stock from a calcareous fen in proximity to a rehabilitation project, with associated additional labour for extraction, as well as potential impacts on the natural fen. The three remaining treatments each consisted of first washing-off the associated peat material from the roots of the ramet plug to be inserted. The 'screenings' treatment involved digging a little opening in a container filled with screenings (*b*-axis of 25 mm), placing the plant roots in this cavity, and patting screenings around the plants for stabilization. The 'topsoil' treatment followed this procedure, but also added a shallow, ~3 cm layer of topsoil on top of the screenings. Thus, these two treatments provided an easy test of the effect of nutrient supply on plant growth: the screenings treatment representing little nutrient addition, the topsoil treatment representing abundant nutrient addition. The addition of topsoil adds a cost to rehabilitation efforts. Plant roots were also placed in containers filled with coarse dolostone cobbles (random packing arrangement and size) for the 'rock' treatment. This treatment represents the least costly implementation protocol with little physical manipulation of the rehabilitation site needed.

The effect of water level on aboveground biomass was tested through three depth treatments (Fig. 1b). Working with the natural slope of the quarry floor, transplant bins were arranged such that springtime water level was at 15 cm below ground level ('shallow' treatment), at the ground surface ('intermediate' treatment), and 15 cm above ground level ('deep' treatment). As the bins were 30 cm deep the shallow treatment consisted of half its potential rooting depth at the beginning of the growing season being unsaturated and aerobic. The intermediate water depth treatment started its growing season with plant roots completely inundated, while the deep treatment was subject to the lower portions of the aboveground biomass being inundated as well. The slope of the ground

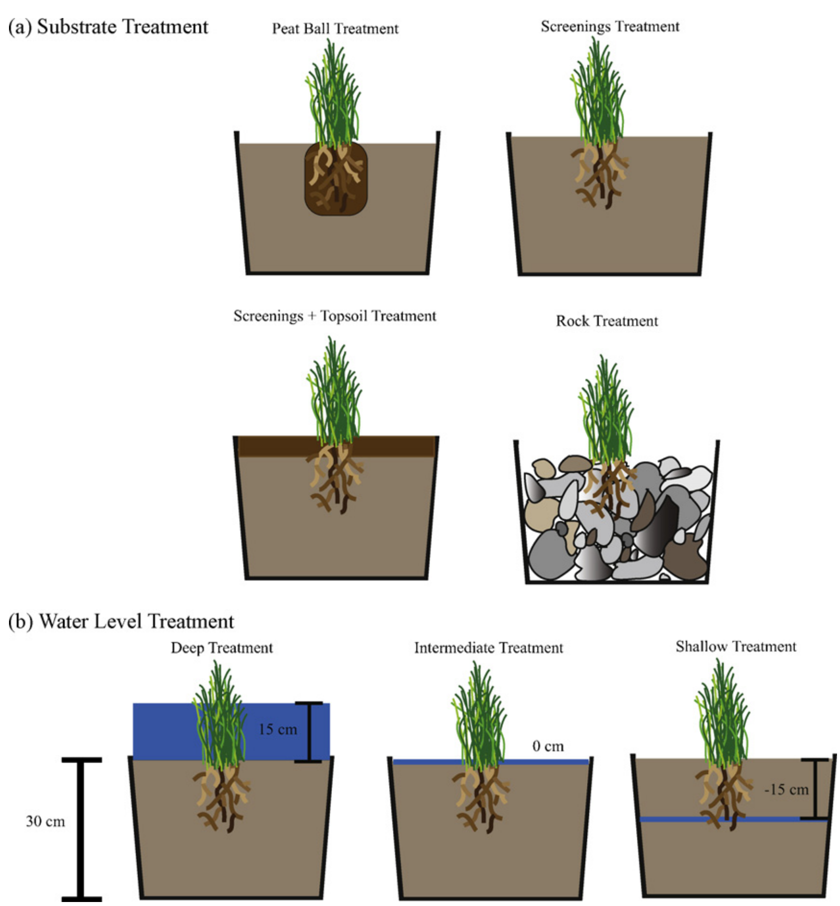


**Fig. 1.** Schematic diagram showing (a) the different substrate treatments and (b) the water depth treatments used in the experiment.

was modified so that within each treatment there was <1.5 cm deviation from the above depths between replicates. At the initiation of the experiment it was not known to what degree the water level in the experimental area would fluctuate. Overall, the water levels of all treatments gradually fell throughout the sedge growing season, not returning to initial, springtime levels until late August at the earliest (2006 growing season), or late September at the latest (2007 growing season).

For each substrate–water depth combination treatment three replicates were created; thus, a total of 36 *in situ* water sedge mesocosms were tested (3 reps × 4 substrate × 3 water levels). For each water depth treatment area the substrate replicates were randomly arranged in a grid of 4 × 3 to minimize any biases in their positioning. The experimental area of the quarry was open, without any shading by surrounding vegetation or quarry walls until approximately 5–6 pm during the growing seasons.

### 3.2. Growth measurements

Plant success was evaluated by monthly measurements of the number of stems in each replicate in the growing seasons of 2005 and 2006, with a final stem count made at the end of the growing season in 2007. Here we use the terms stem and shoot interchangeably, to define an individual culm or stalk, similar to a grass tiller. Each rhizome is capable of producing several stems (Bernard, 1990). Additionally, the number of inflorescences produced per plot was measured at the peak of the growing season in each year. The number of stems represents an index of seasonal growth, while the number of inflorescences can be viewed as an assessment of the reproductive success of the transplants.

Two weeks after the peak of the 2007 growing season, before senescence, the aboveground biomass from each treatment was harvested in the field. At the time of harvest 35 out of 36 plots visually contained >90% areal cover of *Carex aquatilis*. The remaining other plant species were removed during the harvest and not measured. One replicate of the topsoil-intermediate treatment did contain ∼20% *Juncus effusus* (soft rush) by area with ∼78% *Carex aquatilis*. The soft rush was also removed and discounted during the harvesting procedure. The harvested *Carex aquatilis* was dried to a constant mass at 70 °C in the lab and subsequently weighed for a final dry mass.

### 3.3. Data analysis

A three-way fixed effects ANOVA was conducted for the substrate type × water depth × year effects on stem count and inflorescence data. Tukey's LSD test was applied post hoc to determine statistical significance between means. Stem count data were log-transformed and inflorescence data were square-root transformed to improve homoscedasticity and normality of residuals. A two-way, fixed effects ANOVA was conducted to test the effects of substrate type and water depth treatments on the total aboveground biomass from 2007. Post hoc Tukey's LSD test was run to determine statistical significance between means. Total aboveground biomass data were log-transformed to improve homoscedasticity and normality of residuals. All ANOVA's and post hoc analyses were conducted using SYSTAT 12 (Systat Software, 2007).

## 4. Results

### 4.1. Aboveground growth

The different soil and water depth treatments produced a noticeable difference in the *Carex aquatilis* transplants (Fig. 2).

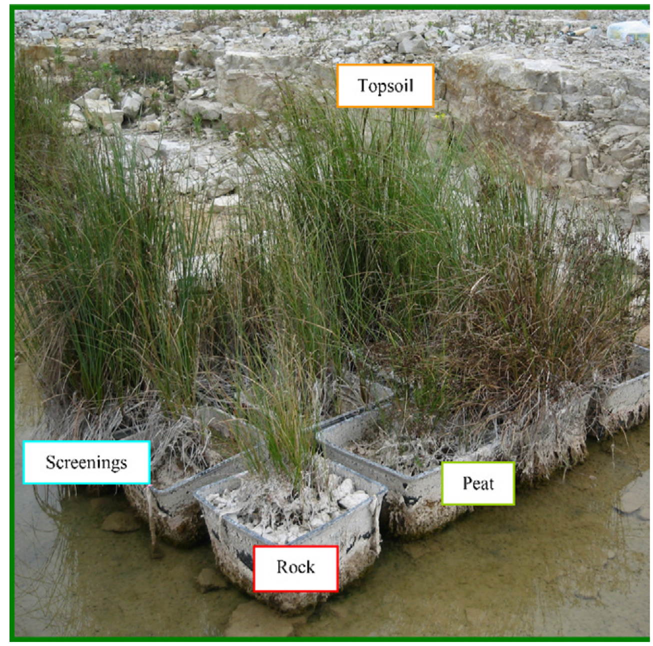


**Fig. 2.** Photograph depicting the intermediate water depth treatment mescosms just prior to harvesting in August 2007.

The results of the three-way ANOVA indicated that there were significant differences in the number of shoots between the substrate types ($p < 0.001$) and growing season ($p < 0.001$), but not water depth ($p > 0.05$, Table 1). There was also a significant interaction effect between substrate type and water level ($p < 0.05$) and between substrate type and growing season ($p < 0.001$). Only the topsoil and peat ball treatments yielded additional *Carex aquatilis* shoots at the end of the first growing season, on the order of a 12% increase (Fig. 3). After the first year of growth, sedges in the rock substrate and screenings substrate treatments generally maintained the number of shoots at time of planting; on average ±1 change in absolute number of shoots. None of the 2005 shoot data were significantly different from one another. The growing season of 2006 resulted in substantial dieback of the sedges in the rock and screenings treatments (−24 and −34%, respectively), as well as moderate decreases (−7%) in the peat ball treatment; however, the number of stems in the topsoil treatments more than doubled (+140%) from the initial numbers, which was significantly greater than the 2005 numbers and the other substrate types in 2006 ($p < 0.001$, Fig. 3). At the end of the 2007 growing season the plants in the peat ball and rock treatments increased in number of shoots

**Table 1**
Effects of substrate type (topsoil, peatball, rock, screenings), water depth (shallow, intermediate, and deep), and time (2005, 2006, and 2007 growing season) on number of *Carex aquatilis* shoots (SHOOT) and inflorescences (INFLR) through 3 years growth. Figures are *F*-ratios and levels of significance from three-way ANOVA.

| Source of variation | df | SHOOT | INFLR |
|---|---|---|---|
| Substrate type | 3 | 50.75$^{***}$ | 32.883$^{***}$ |
| Water depth | 2 | 0.324$^{ns}$ | 1.243$^{ns}$ |
| Year | 2 | 10.359$^{***}$ | 63.587$^{***}$ |
| Substrate × water | 6 | 2.375$^{*}$ | 3.273$^{**}$ |
| Substrate × year | 6 | 8.502$^{***}$ | 13.636$^{***}$ |
| Water × year | 4 | 0.587$^{ns}$ | 1.557$^{ns}$ |
| Substrate × water × year | 12 | 0.587$^{ns}$ | 1.048$^{ns}$ |

$^{***}$ $p < 0.001$.
$^{**}$ $p < 0.01$.
$^{*}$ $p < 0.05$.
$^{ns}$ $p \geq 0.05$.

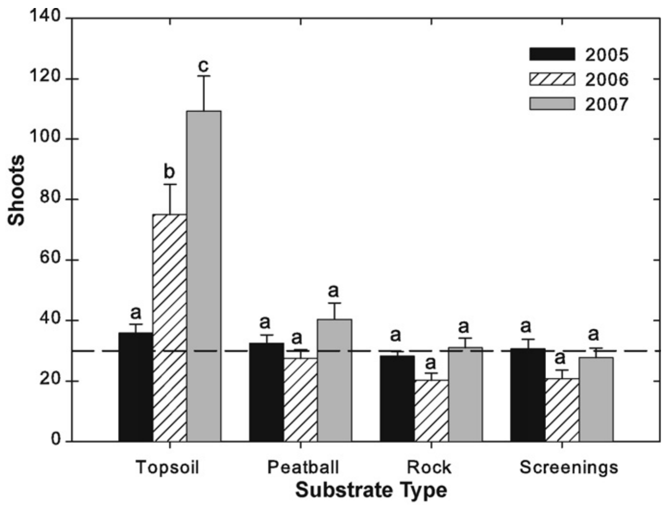


**Fig. 3.** Effect of substrate treatment on *Carex aquatilis* stem numbers over 3 years of growth. Bars are means ± 1 SE ($n = 9$). The dashed line represents the average number of stems per plot at the start of the experiment. Different letters denote significant differences using Tukey's LSD ($p < 0.05$).

from the 2006 growing season (+12 and +15% from initial numbers, respectively), as did the plants in the screenings substrate, but this substrate type contained on average 11% fewer shoots at the end of the third growing season than initial values. At the conclusion of the experiment, only the topsoil-amended treatment displayed a significantly different ($p < 0.001$) number of shoots from the initial conditions, with an overall increase of 250%, which corresponded to an average increase of 80 shoots per bin (Fig. 3).

The effect of water depth was not significant to shoot number when all substrate types and growing seasons were combined; however, there were some significant differences in shoot number within the substrate treatments, as well as qualitative trends to the data (Fig. 4). The topsoil-amended mesocosms performed slightly better in the intermediate water level treatment, with an average 336% increase in shoots at the conclusion of the experiment (Fig. 4a). Between the 2006- and 2007-growing seasons the deep and shallow treatments of the topsoil substrate plots increased the number of shoots from ~85% (relative to initial conditions) to 221 and 195%, respectively. The topsoil-amended, intermediate water level treatment resulted in a significantly greater number of shoots in both 2006 and 2007 from the initial conditions, as did the deep-water treatment in after the third growing season ($p < 0.05$, Fig. 4a).

The effect of water level on the peat ball substrate treatments was more variable (Fig. 4b). At the end of the first growing season the stem counts in the shallow water level treatment had increased by on average 33% (an average addition of 10 new stems), whereas

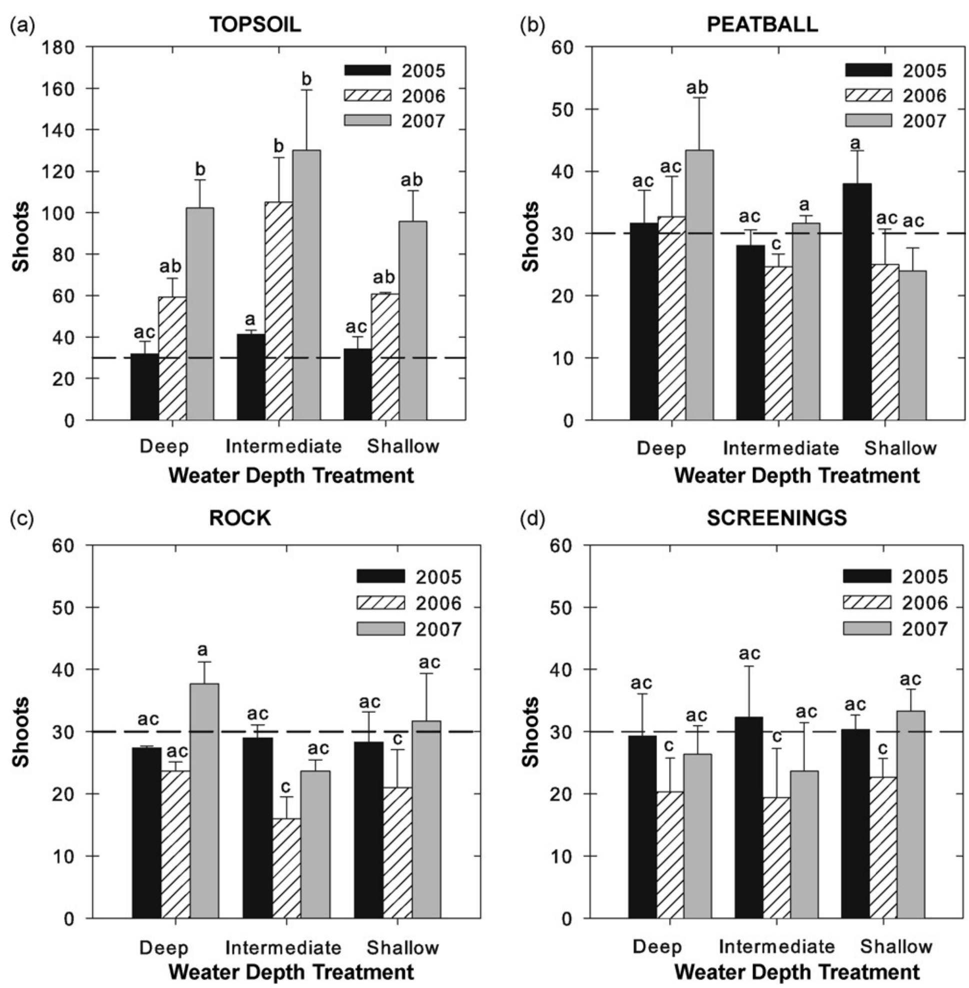


**Fig. 4.** Effect of water depth treatment on *Carex aquatilis* stem numbers over 3 years of growth separated by substrate treatment. Bars are means ± 1 SE ($n = 3$). The dashed line represents the average number of stems per plot at the start of the experiment. Different letters denote significant differences using Tukey's LSD ($p < 0.05$).

the intermediate- and deep-water treatments did not produce statistically any new stems. In contrast, by the end of the third year of growth (2007), the pattern had reversed: the deep-water level replicates had gained on average 11 stems from the initial level (+34%), and the intermediate level mesocosms had increased their number of stems by 17%, while the shallow level replicates had four fewer stems than what they had started with, for a loss of 15%.

The rock and screenings substrate treatments resulted in overall lower shoot additions than those containing some form of organic matter. After 1 year of growth the transplants placed in the rock treatment showed little overall change in growth, with a decrease of 2 (−7%) shoots (Fig. 4c). All water level treatments continued to result in a reduction in the number of shoots in the second year of growth. This effect lasted into the 2007-growing season for the intermediate and shallow water treatments, as while there was on average new growth of 7 and 10 shoots between the 2nd and 3rd growing seasons, these numbers were still 11% less (intermediate water) and an insignificant 2.5% more (shallow water) than the initial levels. On the other hand, the sedges in the rock substrate subject to the deep water had 55% more shoots than at time of transplant, adding on average 14 new shoots per plot between the second and third growing seasons. These data, however, were not statistically significant.

While on average there was only minimal change in the number of shoots in the screenings treatment after the first year's growth, all water depth treatments led to a one-third reduction in the number of shoots at the end of the second year's growth (Fig. 4d). This led to fewer shoots at the end of the experiment than when it began in the screenings treatment; however, between the second and third growing seasons the screenings mesocosms did add on average six, four, and ten new stems in the deep, intermediate, and shallow treatments, respectively.

*4.2. Reproductive potential*

The ability of a vascular plant, particularly wetland sedges, to produce viable reproductive organs and seeds is a key indicator of the successful establishment of vegetation. As the original transplant material was obtained from the natural reference fen at the beginning of the growing season, there were no inflorescences to begin the experiment. Throughout the experiment the *Carex aquatilis* transplants in all treatments produced inflorescences (Fig. 5). The results of the three-way ANOVA indicated that there were significant differences in the number of inflorescences produced between the substrate types ($p < 0.001$) and growing season ($p < 0.001$), but not water depth ($p > 0.05$, Table 1). There was also a significant interaction effect between substrate type and water level ($p < 0.01$) and between substrate type and growing season ($p < 0.001$). There were no significant differences in number of inflorescences between treatments for the first (2005) or second (2006) growing seasons. The 2007 growing season yielded significant differences both within the topsoil treatment and between the

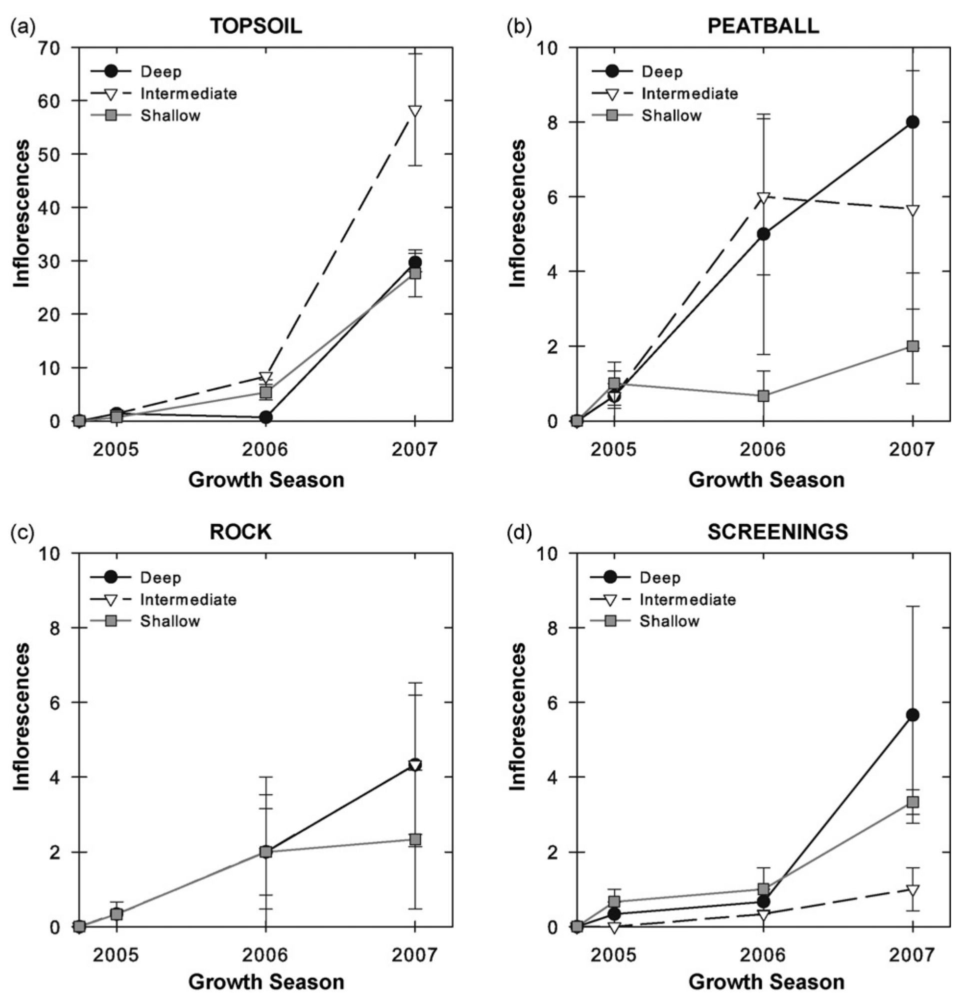


**Fig. 5.** Inflorescence response in field mesocosms between substrate and depth treatments. Data points are means ± 1 SE ($n = 3$). For ease of viewing, significant differences as revealed using Tukey's LSD are not shown (see text for details).

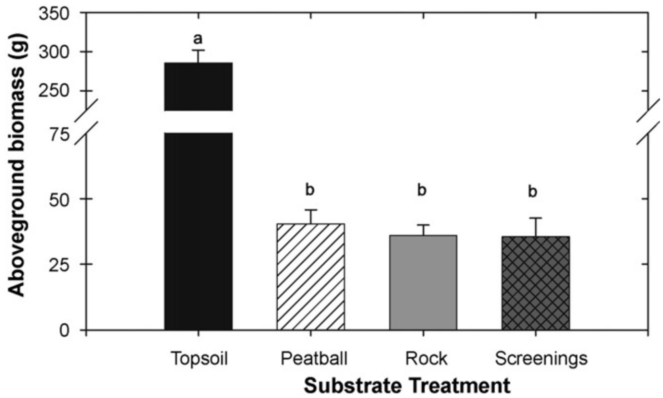


**Fig. 6.** Effect of substrate type on *Carex aquatilis* aboveground biomass after 3 years of growth. Bars represent means ± 1 SE ($n = 9$). Different letters denote significant differences using Tukey's LSD ($p < 0.01$).

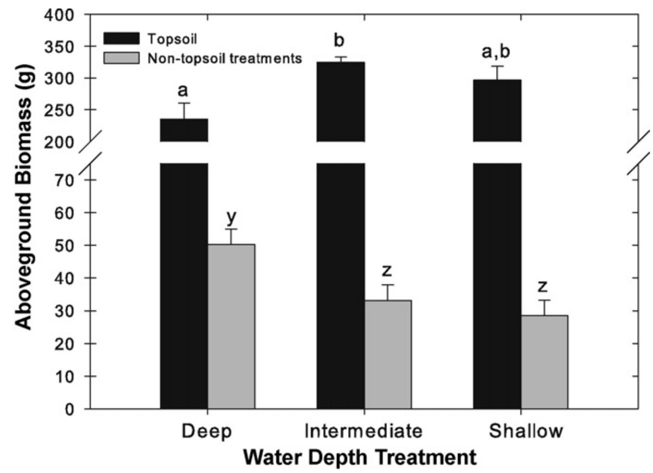


**Fig. 7.** Effect of water depth on *Carex aquatilis* aboveground biomass after 3 years of growth in the topsoil and non-topsoil-amended substrates (data for peatball, rock, and screenings treatments combined). Bars represent means ± 1 SE ($n = 9$ for topsoil treatment, $n = 12$ for combined non-topsoil treatments). Different letters denote significant differences using Tukey's LSD ($p < 0.05$).

topsoil treatments and the non-topsoil treatments. All water depth treatments yielded more inflorescences in the topsoil treatments in 2007 than 2006 ($p < 0.01$). Furthermore, all water depths in the topsoil treatment produced nearly five times more inflorescences than any of the non-topsoil treatments in 2007 ($p < 0.01$). Finally, in 2007 the intermediate water depth for the topsoil treatment produced more inflorescences than either the deep or shallow water depth ($p < 0.001$). The only other significant difference as revealed by the Tukey's LSD was a greater number of inflorescences produced in the screenings deep combined treatments compared to the screenings-intermediate treatment in the 2007 growing season ($p < 0.05$). Combining and averaging all the non-topsoil treatments indicates that increasing saturation led to an increase in inflorescence production per plot, from 2.5 in the shallow treatments in 2007 to 6 per plot in the deep treatments (data not shown).

### *4.3. Aboveground biomass*

At the conclusion of the experiment in August 2007 all treatment plots contained abundant vegetation; however, the topsoil treatments contained substantially more aboveground plant biomass, regardless of water depth treatment (Fig. 6). The results of the two-way ANOVA indicated that there were significant differences in the total aboveground biomass produced between the substrate types ($p < 0.001$) and water depth ($p < 0.05$, Table 2). There was not a significant interaction effect between substrate type and water level. The aboveground biomass in the topsoil treatments averaged 285.7 g per plot, which was nearly an order of magnitude more than the average biomass contained in the peat ball (40.4 g), screenings (35.4 g), or rock (36.1 g) treatments. There were no statistically significant differences between the peat ball, screenings, and bare rock treatments.

Because of the large difference in biomass between the topsoil treatments and the others, the topsoil treatment was separated from the peat ball, screenings, and rock treatments for analysis of the effect of water depth on aboveground biomass. In the no-topsoil treatments, aboveground biomass was significantly greater ($p < 0.05$) in the deep-water treatments than the intermediate and shallow depth treatments, which were not significantly different (Fig. 7). At an average of 50.2 g per plot, the deeper water treatment resulted in more than 50% additional growth of aboveground plant material relative to the intermediate (33.2 g) and shallow (28.5 g) water depth treatments for the no-topsoil substrate types, which was significantly different at the $p < 0.05$ level. On the other hand, of the treatments with added topsoil, those placed in the deeper water (mean = 235.8 g per plot) performed significantly worse ($p < 0.01$) than the intermediate treatment (mean = 324.7 g per plot). The topsoil-amended transplants subjected to a shallow water treatment resulted in a mean aboveground biomass of 296.6 g per plot, which was not significantly different from either the deep or intermediate water treatments.

**Table 2**
Effects of substrate type and water depth on *Carex aquatilis* total aboveground biomass after 3 years growth. Figures are *F*-ratios and levels of significance from three-way ANOVA.

| Source of variation | df | BIOMASS |
|---|---|---|
| Substrate type | 3 | 90.940*** |
| Water depth | 2 | 3.501* |
| Substrate × water | 6 | 2.302ns |

*** $p < 0.001$.
* $p < 0.05$.
ns $p \geq 0.05$.

## 5. Discussion

### *5.1. Plant growth*

Our results demonstrate that flooded abandoned aggregate quarries have the potential to be targets of rehabilitation towards calcareous wetlands. Transplant survival rate was 100% regardless of planting substrate type or springtime water depth. These data are remarkable considering previous attempts of transplant restoration efforts. Fraser and Karnezis (2005) observed 40–100% survival of *Carex* sedge seedlings grown in water depths from 0 to 6 cm below ground surface, but 0–40% survival when grown in 2–6 cm standing water. Our deep-water treatments consisted of 15 cm standing water at the beginning of the growing season. Using rhizomes, Yelka and Galatowitsch (1999) had less than 10% survival for the tussock forming *Carex stricta*, and a mean of 53% springtime transplant survival for *C. lacustris*, though higher survivorship was found when rhizomes were planted just upgradient from the water's edge. It is probable that our high survivorship was due to transplanting a large number of shoots/culms (30) associated with at least one, and probably more, ramets per treatment plot. Ikegami et al. (2009) have suggested that high shoot density in sedges will increase carbon fixation initially for the ramet to later use for rhizome expansion into higher quality habitats. Thus, our data suggest planting mature sedges with a cluster of shoots in a tiller clump rather than farther spaced younger ramets, with limited root density and fewer shoots, may significantly increase wetland restoration efforts, and ongoing work at this rehabilitation site is examining this.

The measurements of shoot numbers suggest little aboveground growth should be expected in the first year post-transplant, as no substrate-water depth treatment combination resulted in shoots significantly greater than zero in the 2005 growing season (Figs. 3 and 4). There is the possibility that growth in 2005 was limited by the time of transplant. We initiated the experiment in mid-May, approximately 5 weeks after sedge leaf-out in the nearby natural site. Steed and DeWald (2003) found that transplanting wetland sedges in semi-arid Arizona riparian meadows was more successful when transplants were made in summer, rather than autumn. By extension to the temperate setting in this study, growth in the first year may have been enhanced with an earlier time of transplant. Furthermore, Steed and DeWald (2003) suggest that much biomass allocation in the first year post-transplant is directed to belowground growth of rhizomes, and had our experiment been destructive after just 1 year to include this portion of biomass, more differences may have been apparent.

The formation of reproductive organs, referred to here as inflorescences, is controlled largely by a combination of photoperiod and temperature (Heide, 1997). Species of the genus *Carex* require a dual phase of short days at the end of one growing season followed by long days at the start of the second, with temperatures in both periods strongly affecting the development of the inflorescences (Heide, 2004). This suggests that nutrient and mineral availability do not affect reproductive potential. If this is true, then the number of inflorescences produced should fall directly in line with the number of shoots produced in all mesocosms as they were subject to the same photoperiod and presumably the same air temperature. Our data suggest that there may be factors other than day length and temperature, as in the topsoil-amended treatments mean shoot numbers increased from a mean of 75 ($\pm$10.1) to 109 ($\pm$11.4) between the second and third growth season (less than a doubling in numbers), whereas the number of inflorescences increased nearly eightfold, from 4.8 ($\pm$1.2) to 38.6 ($\pm$6). In the other treatments inflorescence addition did closely mimic shoot addition. Based on our data we cannot determine the controls on this great rate of change in the topsoil-amended treatments, but it is likely to either be due to the added nutrient availability, an insulating effect of the topsoil, or the physical limitation of space associated with the large number or shoots per mesocosm.

After 3 years of growth there was significant aboveground biomass of *Carex aquatilis* in the mesocosms. Converting the mass per mesocosm, with an area of just 0.09 $m^2$, to a unit area weighting, the topsoil treatments produced on average 3174 $g\,m^{-2}$, and on average 448, 393, and 401 $g\,m^{-2}$ in the peatball, screenings, and rock treatments, respectively. We did not harvest any material from the nearby natural fens, but comparison with literature values indicates these data are very high. In an experiment on nutrient enrichment on biomass in rich fens of Norway, Øien (2004) found control plots contained on average 140 $g\,m^{-2}$ of all vascular vegetation, with little response of sedge biomass to fertilization. Standing biomass of *Carex limosa* (L.) in a poor fen and *Carex lasiocarpa* (Ehrh.) in a calcareous fen in Alberta, Canada averaged just 16.5 and 74.6 $g\,m^{-2}$, representing 5 and 50% of total aboveground biomass, respectively (Glenn et al., 2006). In a calcareous fen in the Netherlands, total aboveground biomass ranged from 400 to 600 $g\,m^{-2}$ depending on position and growth season, with the most frequent sedge at that site, *Carex panicea*, comprising 25–50% of the stock (Van der Hoek et al., 2004). It seems even our least successful treatments yielded biomass values on the high end of what is found in natural settings, with the addition of topsoil producing perhaps the highest aboveground biomass as yet determined. The most likely explanation for these findings is the lack of resource competition with other species in the mesocosms. It does, however, definitively answer our question as to whether calcareous fen species can grow and thrive in abandoned aggregate quarry settings.

It should be noted that all of the results should be treated as less than maximum potential aboveground biomass values. During the vegetation harvesting in August 2007 it was noted that the roots of the sedges had grown out of the plastic containers in 33 out of 36 mesocosms. Indeed, more than half the mesocosms had roots that had anchored in to the underlying dolomite bedrock, presumably through crevice formation by active dissolution of the parent material (Ford and Williams, 2007). Furthermore, in the combination treatment that produced the greatest aboveground biomass, the intermediate water depth $\times$ topsoil treatment (Fig. 7), the relative rate of shoot addition decreased between the second and third growing season compared to the other topsoil treatments (Fig. 4a), suggesting that the intermediate-depth topsoil mesocosms were approaching their maximum carrying capacity. Thus, it is valid to suggest that in our experiment *C. aquatilis* growth was limited by the container size in at least the third growing season, and aboveground biomass values may have been greater if the sedges were not so confined. There may have been differences in the belowground biomass between substrate and/or water depth treatments, but an accurate analysis could not be made due to the difficulty separating the fine roots from the substrate matrix in the large containers.

### 5.2. Soil matrix

We were incorrect in our hypothesis that the peatball treatments would prove most successful; these treatments statistically did no better than either the rock or screenings treatments (Figs. 3–6). Furthermore, we did not expect the addition of just a few centimetres of topsoil to produce a near order of magnitude increase in shoots, inflorescences, and aboveground biomass after 3 years of growth. As our overall objectives are to transform an abandoned aggregate quarry to a stable calcareous wetland in the long term, this suggests that the addition of a moderate amount of topsoil can significantly enhance short-term ($\leq$3 years) stabilization and growth of vascular plants. That is, while procurement and addition of topsoil represents an added up-front cost to quarry rehabilitation projects, our data provide evidence that the rapid growth and expansion of the transplanted vascular plants may offset these added costs.

*Carex*-dominated wetlands are particularly well adept at internal nutrient cycling (Bernard and Solsky, 1977; Auclair, 1982; Aerts et al., 1999); therefore, it is probable that this initial addition of organic-rich soil would not need replenishment. Another possible strategy for quarry rehabilitation projects would be to construct a mosaic of surficial soil types, consisting of various mixtures of organic and mineral contents. As the species present is expected to be different depending on amount of organic matter and nutrients added, it is suspected that this approach may lead to a richly structured community (Amon et al., 2005).

On the other hand, over the long term (>10 years), the addition of topsoil and its associated high nutrient levels renders the rehabilitated community more susceptible to invasion and subsequent loss of biodiversity value. Indeed, after 3 years of growth the only treatment mesocosm to display evidence of invasion was a topsoil-amended replicate. Nutrient enrichment in peatlands through degradation and subsequent restoration efforts can affect the natural vegetation community structure (Wind-Mulder et al., 1996). High nutrient levels have been shown to increase the likelihood of invasion of both *Typha* spp. and *Phalaris arundinacea* in natural wetlands and restoration projects (Wetzel and van der Valk, 1998; Green and Galatowitsch, 2002; Perry and Galatowitsch, 2003; Wilcox et al., 2008). Over the last 4 years we have observed increasing numbers of *Typha latifolia*, *Phalaris arundinacea*, and *Phragmites australis* in the natural calcareous fens adjacent to the quarry rehabilitation property, most likely due to increasing nitrate levels in the source water (Duval, unpublished data). While the long-term effects of topsoil addition were not the focus of this study, we acknowledge the possibility that this treatment option could lead to invasive species, and warrants further study.

Based on the results of the experiment, there was no added benefit to a prescription of crushing the bedrock material to the level of fine material prior to transplanted ramet insertion. That is, coarse cobble material did not reduce seasonal shoot growth, inflorescence production, or final biomass totals relative to the transplants inserted in the fully crushed screenings, as we hypothesized (Figs. 3–6). This is supported by visual observations of the belowground structure of the mesocosms: after 3 years of growth, nearly all of the cobbles had been crushed down to the size of coarse gravel by the sedge roots. It is suspected that this provides increased mineral (calcium and magnesium) nutrition to the plant through increasing the surface area of contact for the roots.

### 5.3. Water depth

Overall, the effect of water depth proved less of a factor on transplant success than the substrate effect. We were unable to support our hypothesis that the intermediate water treatment would produce the greatest growth in *C. aquatilis* transplants. In part this is due to the overwhelming influence of the topsoil addition, but there was also little difference in sedge response to water levels in the other substrate treatments. These findings are in line with previous research (Kotowski et al., 2001; Güsewell et al., 2003; Wetzel and van der Valk, 2005) and suggest wetland sedges are able to grow in a range of water levels (30 cm range in this study) in restoration projects.

It is suspected that the topsoil-amended mesocosms placed in the deep-water treatment resulted in lower aboveground biomass than the other water depth treatments due to the suspension within the water column and subsequent displacement of some of the applied topsoil; that is, a loss of nutrients in the deep treatment. Indeed, this re-suspension may have been the reason for the increased biomass in the peatball, rock, and screenings deep-water treatments compared to the other water depths (Fig. 7). Based on these findings the application of topsoil may not be as cost-effective in portions of quarries targeted for rehabilitation that are subject to appreciable levels of standing water for much of the growing season.

## 6. Conclusion

Our data demonstrate the effectiveness of transplanting *Carex aquatilis* ramets to abandoned aggregate quarry sites with discharging calcareous groundwater. Our design employed minimum maintenance of the site, and is following a trajectory of ecosystem self-design. This study indicates that these impacted landscape settings, which are common in southern Ontario, can easily be rehabilitated to calcareous wetlands. Three measures of growth indicated that the addition of a thin layer of topsoil resulted in an order of magnitude increase in transplant success. As a cost-effectiveness strategy, we conclude that this minimal added measure significantly increases the restoration success. Alternatively, we show that the sedge material at least maintained, and demonstrated a gradual increase to, the initial transplanted stock after three seasons grown in mineral substrate. Our data also demonstrate that *Carex aquatilis* ramets are capable of growing in springtime water levels from 15 cm above to 15 cm below ground surface, illustrating that this sedge species can grow in a range of quarry restoration sites. Ongoing research is examining long-term trends post-transplant, including organic matter accretion, as well as the controls on community establishment and the suitability of ramets, seedlings, rhizomes, and seeds as suitable restoration media in these mineral calcareous settings.

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